AD647228

COST EFFECTIVENESS IN SHEET-STEEL BULKHEAD REPLACEMENT, MAINTENANCE, AND REPAIR

Prepared for:

Eastern Division
Naval Facilities Engineering Command
New York, New York

Contract: N62519 67C 0040 (NBy 77589(ES))

Work Unit: Y-F015-15-07-004

Prepared by:

Peat, Marwick, Livingston & Co.
2050 Tower Building
Prudential Center
Boston, Massachusetts

December 31, 1966

Distribution of this document is unlimited.

ABSTRACT

Presented in this report are the results of a study to determine what materials and methods can be economically used in sheet-steel bulkhead installation, maintenance, and repair. Several materials and methods are investigated to determine if their use will aid in extending bulkhead life. Mathematical models of the cost of application of the more promising systems are compared with the cost of a carbon steel bulkhead. Eight systems that appear to be cost effective are examined in detail. The most favorable conditions for use of these systems are discussed, particularly in reference to bulkhead maintenance and repair work that was concurrently conducted at the Naval Air Station, New York.

FOREWORD

This research and analysis was conducted under Contract No. N62319 67C 0040 (NBy 77589(ES)) from August 31, 1966, to December 31, 1966. The project was administered for the Eastern Division, Naval Facilities Engineering Command, by Mr. Bernard Lewis, and the coordinator for the U.S. Naval Civil Engineering Laboratory was Mr. Joseph A. South. The cooperation of these gentlemen and several of their associates is gratefully acknowledged. Work on this project was supervised by Mr. Kenneth G. Fettig of Peat, Marwick, Livingston & Co. Technical and administrative aid was provided by Professor Russel C. Jones of the Massachusetts Institute of Technology.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont.)

LIST OF ILLUSTRATIONS (Cont.)

LIST OF ILLUSTRATIONS (Cont.)

I. INTRODUCTION

For several years, the Naval Facilities Engineering Command (NFEC) has used sheet-steel piling for bulkhead walls in shoreline environments. Sheet-steel piling has proved to be a fast, relatively inexpensive means of developing a semi-impervious shoreline structure for channels, docking facilities, beach stabilization walls, and sea walls. For this reason, it has been used extensively in bulkheads installed during periods of rapid mobilization, such as World Wars I and II. A significant portion of the sheet-steel piling bulkheads now in service was placed during World War II, and because these bulkheads have had little systematic maintenance, they show significant deterioration.

The prevalence of deteriorated bulkheads requires an immediate course of action. The alternatives are:

- replacement of deteriorated bulkheads with the same material or alternative materials;
- repair of the bulkheads to substantially extend functional life;
- periodic maintenance to prevent or retard further deterioration; or
- allow deterioration to continue and replace as necessary.

Because of the volume of work that may be necessary, funding limitations must be considered in determining the best course of action.

The Eastern Division has taken several steps toward formulation of a bulkhead maintenance policy, including:

- investigation of repair techniques that will extend the functional life of a bulkhead by some period of years;

- contracting for four types of experimental repair work on bulkhead sections of the U.S. Naval Air Station in Brooklyn, New York (NAS(NY)); and

- evaluation of coating material applications to existing bulkhead walls.

This report documents a study that was undertaken by Peat, Marwick, Livingston & Co. to investigate the opportunities for greater cost effectiveness in sheet-steel bulkhead replacement, maintenance, and repair. This report discusses the following:

- the wide range of materials and methods that can be used to construct, maintain, and repair bulkheads in shoreline environments;

- the conditions at the site that would affect the choice of a material system or construction methods;

- the field of alternative choices for bulkhead construction, maintenance, and repair; and

- the economics of bulkhead installation.

In keeping with the Navy's desire for maximum cost effectiveness and the limited availability of funds for maintenance efforts, cost profiles are presented in this study that can be used as guides in making decisions on replacement, repair, or maintenance of bulkhead projects.

The study documented in this report was conducted without regard to a particular bulkhead location to ensure that no material or method was eliminated from consideration because of specific locational factors. However, the conclusions drawn are developed from conditions in the Eastern Division, NFEC.

II. SUMMARY

During this study, a number of materials and methods were surveyed with the objective of developing opportunities for greater cost effectiveness in sheet-steel bulkhead replacement, maintenance, and repair. The difficulty in discovering new and more efficient materials and methods emphasizes the basic fact that carbon sheet-steel piling is an efficient, relatively inexpensive material for bulkhead construction. The one major disadvantage in the use of carbon sheet-steel piling is its poor corrosion resistance, which, under normal conditions, will result in functional failure in 20 to 30 years.

The alternative systems that appear to be cost effective in bulkhead construction materials are steel, concrete, timber, and stone. These materials can be fortified by natural and synthetic coatings and by cementing agents, and in the case of steel, cathodic protection can be applied. Each of these four basic materials has properties that make it the most desirable construction material in one of the environmental zones along a bulkhead from the mud line to the shoreline elevation. Combinations of these materials, as well as single material systems, were investigated and found to be applicable in bulkhead replacement, maintenance, and repair.

A replacement system for a carbon steel piling bulkhead must fulfill the same requirements at a lower cost. Several material systems were found that provided longer life, but were not cost effective because of high initial cost. Two systems were found to be cost effective in comparison with carbon sheet-steel piling for bulkhead construction. They are:

- special steel piling for marine applications; and

- rip-rap bulk walls.

Each has certain limitations that preclude universal use, and the environmental factors should be considered prior to the selection of either in preference to carbon steel piling.

Some protection methods applicable to carbon steel bulkheads at installation proved to be cost effective. Two methods explored at length were:

- cathodic protection; and
- impervious organic coatings.

Each of these methods can be applied during construction at a cost increment of less than 10 percent above normal cost. Each method appeared to extend life by 5 or more years, which will ordinarily justify their use. The combination of these two methods may offer additional life extension, but this combination is only marginally cost effective.

Maintenance for sheet-steel bulkheads must be inexpensive and effective in extending bulkhead life. The following two techniques met these criteria:

- coating applications at intervals of several years; and
- grouting or concrete patching as required.

These two methods can be used periodically to extend life, but the amount of time between the maintenance work must be selected to maximize protection against corrosion while minimizing application costs. Annual maintenance for bulkheads does not appear to be efficient. Five years appears to be the minimum period between maintenance projects for the optimum protection at lowest cost.

Three repair techniques for sheet-steel bulkheads were found to be cost effective. They are:

- concrete reinforcing on the steel side;
- concrete replacement of steel in the tidal zone; and
- composite construction of timber sheeting, concrete, and steel.

These techniques utilize the structural strength of the relatively uncorroded sections of steel in the existing steel piling and strengthen the piling with new materials in areas of advanced corrosion. The cost of these repair techniques is 50 to 75 percent of the cost of new carbon steel bulkhead replacements, but life extension in some cases approaches the functional life of a carbon steel bulkhead replacement.

The cost effectiveness of several materials and methods, which might be used in bulkhead construction, is limited by technological and economic barriers. Development of new facing systems, new composite materials, and new underwater application methods could result in more efficient bulkhead systems. Research into these areas is warranted.

III. METHODS AND MATERIALS USED IN BULKHEAD CONSTRUCTION

The three types of bulkheads considered in this report can be identified in terms of their structural configuration as follows:

. cantilever systems;
. anchored systems; and
. bulk walls.

The simplest cantilever system is a bulkhead wall consisting of a line of sheet piling that is sufficiently embedded below the dredge line to resist the overturning forces caused by the upland fill without assistance from a tieback. Use of such a cantilever wall is limited to sites with relatively shallow water, low embankment height, and low surcharge loadings on top of the retained earth. A second type of cantilever system employs discrete soldier piles for lateral resistance, with sections of sheet piling or lagging between soldiers.

For greater bulkhead heights or higher earth pressures, anchored systems are generally used. An anchored bulkhead consists of a wall of sheet piling embedded below the dredge line and restrained near the top by an anchorage system to prevent outward movement. The anchorage system is typically a series of discrete anchors used to tie back a wale fastened to the piling and extending the length of the wall. When heavy surcharge loads are to be supported or a great depth of water is required at the face of the bulkhead, the bulkhead may be constructed with a relieving platform to reduce the lateral effects.

Bulk walls are generally massive gravity structures designed to resist both the lateral earth pressures and the wave action of the sea. They may be vertical, or they may have a curved or stepped face. When a wave breaks on a bulk sea wall, the energy moves the water downward with a force that erodes the sand at the toe of the wall. Bulk walls, therefore, must be carried to sufficient depth to protect the stability of the wall and its retained earth.

Several alternative materials are available for construction of these bulkheads. The traditional materials include steel, concrete, timber, and stone. In the following pages of this section, various alternative systems for initial installation of shore-protection bulkheads are described. For the purposes of this report, the alternative systems have been grouped by basic material of construction, and the types of bulkheads appropriate for each material are treated within the discussion on that material.

A. Steel Piling

Bulkheads of metal consist of a series of rolled sections imbedded into the earth and interlocked to form a cantilevered or anchored wall. Sheet-steel piling—the traditional material used for metal bulkheads—is produced in three shapes and in graduated weights to economically meet various design requirements. The three shapes—straight web, arch web, and Z piling—have interlocking edges, which are continuous throughout their entire length. A typical anchored sheet-steel piling installation is illustrated in Figure 1.

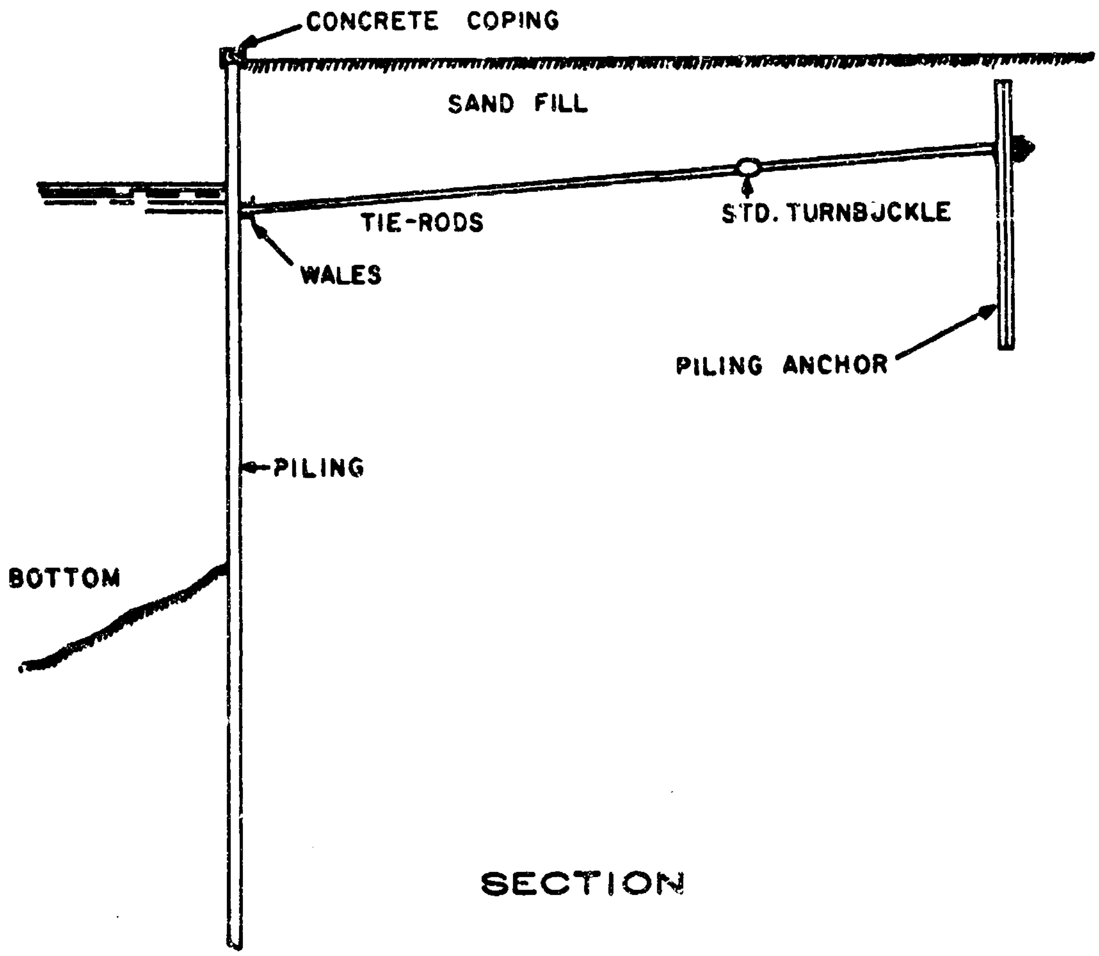
Carbon Steels

Conventional sheet-steel piling is produced from carbon steel alloys conforming to ASTM Specification A328. These steels have a minimum yield stress of 38,500 psi, a minimum tensile strength of 70,000 psi, and an allowable design working stress of 24,000 psi. Conventional sheet-steel piling installed in sea water has often been used without any form of protective coating and has provided reasonable lengths of service, even though serious corrosion has occurred under such circumstances.

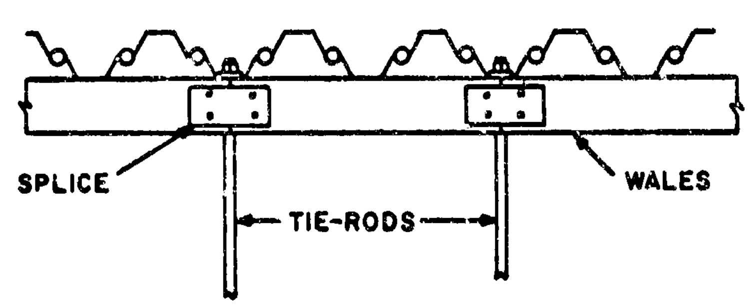
Sheet-steel piling in sea water installations is exposed to differing conditions in the following six zones along its height:

- atmospheric zone;
- splash zone;
- tidal zone;
- active electrolytic zone;
- underwater zone; and
- imbedded zone.

In the atmospheric zone, the steel is subjected to attack by airborne corrosives, and if the steel is unprotected, the normal oxidation process results in rusting. In the splash zone, the corrosion process is similar, but is greatly accelerated by the presence of a thin film of sea water. The corrosion process is an electrochemical reaction in which iron ions combine with the oxygen and hydrogen in the water



SECTION



BULKHEAD DETAIL

FIGURE I - TYPICAL ANCHORED STEEL BULKHEAD

and the air to form rust. Since a good electrolyte is present in the sea water and there is a plentiful supply of oxygen available from the air, corrosion proceeds at a high rate in the splash zone. In the tidal zone, the steel is generally subject to less severe corrosion than in the splash zone because of the periodic submergence of the steel, which results in a decreased oxygen supply in comparison with the splash zone. In addition, the steel in the region very near the water surface is cathodic to an area some distance below the water surface.

Because of continual wave action, the water near the active electrolytic zone normally retains a considerably higher entrapped oxygen content than water at greater distances from the surface. This situation leads to the formation of an oxygen concentration cell, in which the area where oxygen is less available becomes the anode, and the cathode is formed where oxygen is abundantly available. Iron ions continually go into solution in the sea water electrolyte at the anode, thus leading to a gross loss of metal in the region just below the oxygen-rich surface layer. This concentration cell can be controlled by the use of cathodic protection, a modification to the electrochemical system which overrides the concentration cell by imposing a current between the sheet-steel piling and a sacrificial anode. (See Section IV for a detailed discussion of cathodic protection.)

Below the active electrolytic zone, the corrosion rate is relatively small. This region is continually wet, and its oxygen content is uniformly minimal. In circumstances where loose material is transported along the ocean bottom by water currents, however, substantial erosion may occur. The portion of the steel piling embedded in the mud is generally protected against both corrosion and erosion by the mud, with the possible exception that abrasion sometimes occurs during driving, causing minor losses of metal.

To present a quantitative comparison between corrosion rates in the six zones, corrosion rate profiles from several sheet-steel pile installation sites are shown in Figure 2. It can be seen that corrosion rates in unprotected sheet-steel piling are highest in the splash zone and in the active electrolytic zone a few feet below mean low water (MLW).

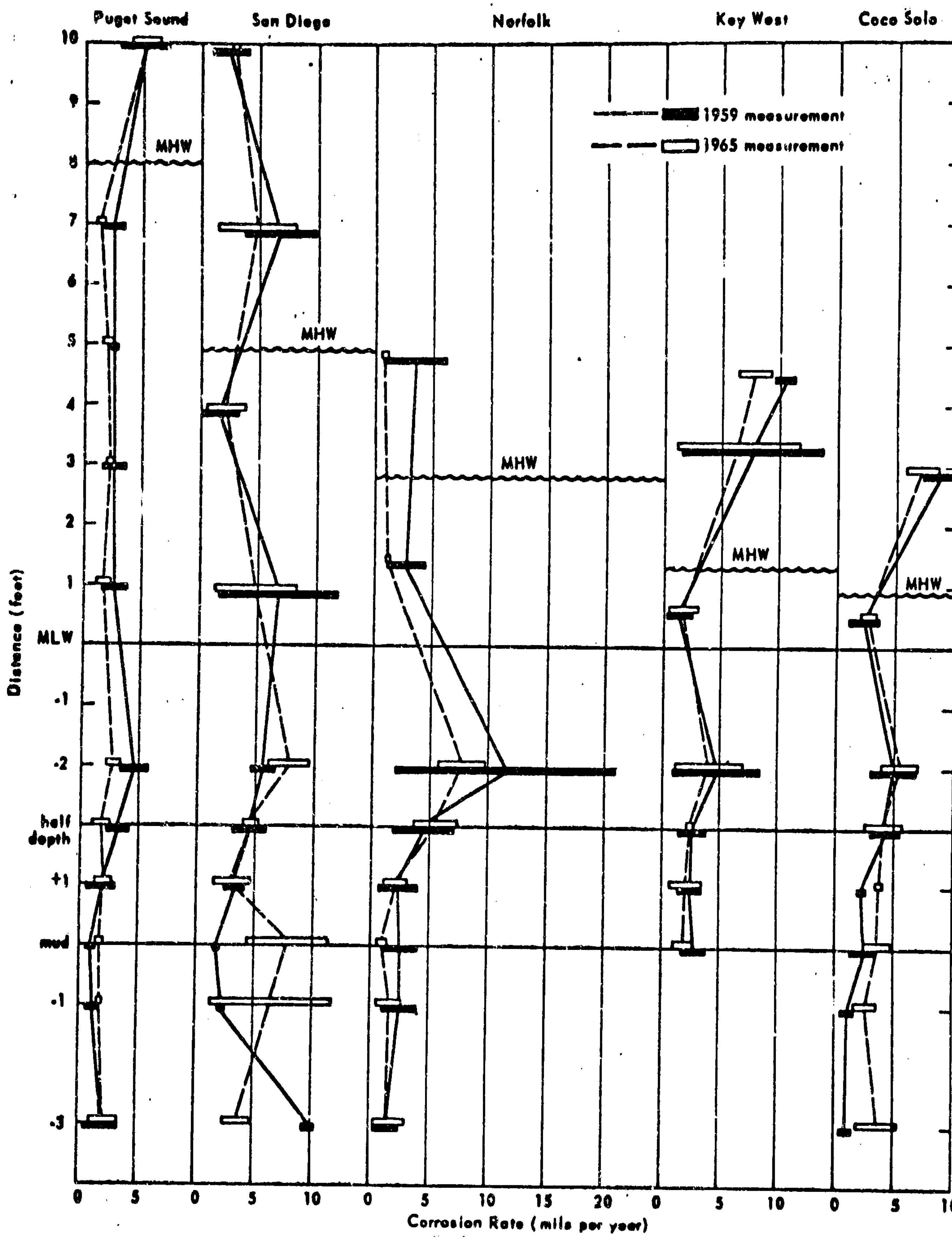


FIGURE 2 — TYPICAL CORROSION RATE PROFILES FOR SHEET-STEEL PILING

("SECOND CORROSION SURVEY OF SHEET-STEEL PILING" - BY BROUILLETTE & HANNA)

It should be noted that local severe corrosion of sheet-steel piling does not necessarily result in catastrophic failure of the bulkhead structure. Even local perforation of the bulkhead piling in the splash zone or active electrolytic zone leaves substantial portions of the bulkhead relatively intact. One beneficial factor in anchored bulkhead design is that maximum bending stresses generally occur at a point below the areas where corrosion most weakens the sheet piling. Stresses may go above the design working stresses as material losses occur, but catastrophic failure will not occur until the safety factor has been used up and the ultimate strength of the steel is exceeded. Local perforation may, however, lead to loss of backfill material, and if this condition is seriously detrimental to the function of the bulkhead, corrective measures will be required aside from structural considerations.

High-Strength Steels

In the late 1950's and early 1960's, a new family of steels was added to the traditional carbon steels: low-alloy steels characterized by higher strengths and, therefore, higher allowable working stresses. Typical mechanical properties for high-strength steel used for sheet piling are of a minimum tensile strength of 70,000 psi, a minimum yield strength of 50,000 psi, and a working stress of 30,000 psi. It should be noted that this working stress is 25 percent higher than that for carbon steels, so that a given sheet piling section will have greater moment-carrying capacity. Figure 3 illustrates, for three grades of high-strength steel, the increase in moment-carrying capacity for a number of typical sheet piling sections.

The high-strength steels cost approximately 15 percent more than carbon steels, but this cost disadvantage can be outweighed by the increase in load-carrying capacity. With respect to corrosion, however, the high-strength steels have no advantage over the carbon steels. In sheet piling applications, in fact, corrosion and erosion can have a more damaging effect on high-strength steel piling. Since high-strength steel piling sections are relatively thinner than carbon steel piling for the same moment-carrying capacity, a loss of a given number of mils of steel because of corrosion will effect a greater reduction in load-carrying capacity in high-strength steel piling.

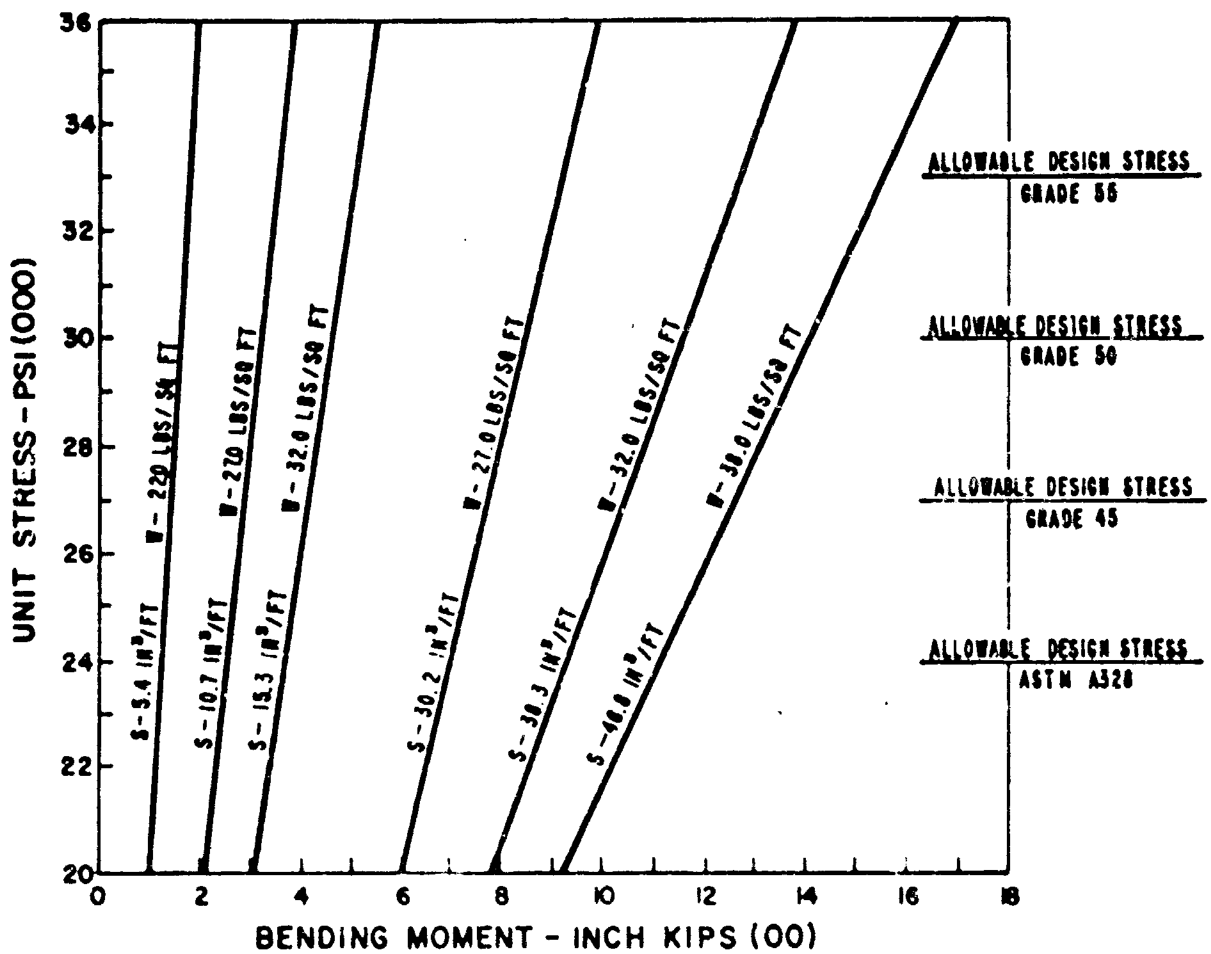


FIGURE 3 - COMPARISON OF MOMENT-CARRYING CAPACITIES OF HIGH-STRENGTH AND CARBON SHEET-STEEL PILING SECTIONS

Special Steel for Marine Applications[1]

Since 1964, an additional type of steel has been available for sheet piling applications: a nickel-copper-phosphorus alloy. This special steel was developed to meet the problem of corrosion in the splash zone, one of the two critical zones where the corrosion rate is particularly high (see Figure 2).

The basic approach to protection from excessive corrosion in this special steel is the use of a corrosion product formed early in the lifetime of the sheet piling to provide a protective coating against further corrosion. The difference between this process and the usual rusting of steel is that in the special steel, the corrosion product forms a dense, continuous, tightly adhering covering on the surface of the steel. Both the dense, continuous nature of the corrosion product coating and the fact that the coating is tightly bonded to the surface are necessary conditions for minimization of additional corrosion.

Comparison of this special steel with standard ASTM A328 carbon sheet-steel piling in actual marine environments shows that the special steel has two or three times greater corrosion resistance in the sea water splash zone. In addition, special steel has the second advantage of increased strength. The special steel is a high-strength steel with 50,000 psi minimum yield stress and thus has greater moment-carrying capacity than a carbon steel piling of the same size and shape. The working stress for special steel is 30,000 psi, which means that it has the same moment-carrying capacity as high-strength, low-alloy steel of 50,000-psi yield strength.

The special steel for marine applications alleviates the splash zone corrosion problem to a major extent, but it does not control the corrosion rate in the active electrolytic zone. It should be noted that application of coatings and cathodic protection to alleviate the high rate of corrosion .

---

[1]A description of this steel can be found in Budocks Notice 11,410, dated December 1964.

in the zone just below the water surface and the use of special steel as the structural material to control the splash zone corrosion problem provide a good combination for promotion of long life for the sheet piling. Coating applied to the piling before driving, can be expected to protect the steel from the oxygen concentration cell attack for three to seven years. At the time of installation of the bulkhead, provision can be made for later installation of a cathodic protection system when the initial protective coating has ceased to be effective in the active electrolytic zone.

This special steel for marine applications has two measurable advantages in addition to the major protection offered in the splash zone. An impermeable and strongly adhesive corrosion product is developed in the atmospheric zone of the piling as a result of initial corrosive attack from atmospheric agents common to industrial areas. This layer of corrosion product protects the base steel from further corrosion. Also, if paint is applied to this steel upon initial installation to prolong the life of the piling or for aesthetic reasons, it will last roughly twice as long as the same coating would on conventional carbon steel piling. This benefit is derived from the low volume and consistent thickness of the corrosion product, which in contrast to carbon steel, is not disruptive to the paint or other coating in the vicinity of the scratch or other break in the coating.

B. Corrosion-Resistant Structural Metals

Several metals having the same strength and stiffness values as the structural steels have considerably better resistance than steel to corrosion attack in sea water. A first approach to identifying materials that might fall into this category can be made by employing the galvanic series in sea water (see Figure 4 for a listing of metals in order of their relative potential for corrosion in sea water). Any material above mild steel on this galvanic series would be a candidate for use as the structural metal from which bulkheads could be constructed, if the material also met the criteria of necessary strength and stiffness and were available at reasonable cost. Several of the more promising corrosion-resistant metals with good structural properties are listed in Figure 5. The detailed corrosion behavior of each of these structural metals is discussed below.

Stainless Steel

Alloying is an effective means for improving the resistance of metals to attack by corrosive environments. Alloying is particularly effective in improving corrosion resistance if passivity results from the combination of a metal that is otherwise active with a normally passive metal.[1] For example, iron alloyed with chromium becomes passive through the process of self-corrosion. In homogeneous single-phase alloys, passivity usually occurs above a limiting composition that is specific to each alloy and may also be dependent upon the environment. For iron alloyed with chromium, the critical composition for passivity comes at about 12-percent chromium. Ferrous alloys having at least this amount of chromium are approximately as passive as chromium itself and are called stainless steels.

---

[1]A metal that is normally active in the galvanic series or an alloy composed of such metals is called passive when its electrochemical behavior becomes that of an appreciably less active metal. Passivity may be due to a thin film such as an oxide, an adsorbed film of oxygen or other gas or of ions, or it may be due to the electron configuration of the atoms.

Figure 4

GALVANIC SERIES IN SEA WATER

Protected end (noble, cathodic)	Platinum
	Gold
	Graphite
	Silver
	18-8-3 Stainless steel, Type 316 (passive)
	18-8 Stainless steel, Type 304 (passive)
	Titanium
	13% Chromium stainless steel, Type 410 (active)
	67Ni-33Cu alloy
	76Ni-16Cr-7Fe alloy (passive)
	Nickel (passive)
	70-30 Cupro-nickel
	Bronzes
	Copper
	Brasses
	76Ni-16Cr-7Fe alloy (active)
	Nickel (active)
	Tin
	Lead
	18-8-3 Stainless steel, Type 316 (active)
	18-8 Stainless steel, Type 304 (active)
	13% Chromium stainless steel, Type 410 (active)
	Cast iron
	Wrought iron
	Carbon steel
	Aluminum 2024
	Cadmium
	Alclad
	Aluminum 6053
	Galvanized steel
	Zinc
Corroded end (active, anodic)	Magnesium alloys
	Magnesium

Figure 5

PROPERTIES OF CORROSION-RESISTANT STRUCTURAL METALS

Metal	Example	Corrosion Rate in Sea Water (mpy)	Modulus of Elasticity (psi)	Tensile Strength (psi)
Stainless Steel	Types 316, 317 (pit-resistant alloys containing molybdenum)	<0.1	28×10^6	85,000
Aluminum Alloys	6061 (aluminum-magnesium -silicon alloy)	<1.0	10×10^6	18,000
Nickel Alloys	54Ni - 16Mo - 16Cr	<0.1	30×10^6	120,000
Copper Alloys	Aluminum Bronze (8% Al)	<0.2	18×10^6	75,000
Titanium	Pure Metal	<0.1	17×10^6	60,000
Mild Steel	A328 Sheet Piling	20.0	30×10^6	70,000

The corrosion resistance of the stainless steels is due to the formation of a thin passivating film on the metal surface. Such a film forms spontaneously from contact of a clean metal surface with dry air for a period of several days, or from short time-exposure with an oxidizing agent such as nitric acid. When the passivated surface is immersed in water containing oxygen, a dynamic equilibrium is set up between breakdown and repair of the film. Maintenance of passivity requires the continuous replenishment of the oxidizing agent. Dissolved oxygen in sea water is sufficient to maintain passivity on clear surfaces, but the metal becomes active in areas where repair of the film is prevented by lack of access to oxygen. Thus severe corrosion and pitting of stainless steel, comparable with that of iron or mild steel, can take place beneath debris, barnacles, or in crevices.

Although stainless steel is usually not attacked galvanically, it may accelerate attack on a less noble metal to which it is connected because of its strongly cathodic nature. In sea water, stainless steel behaves like any other cathode material in causing galvanic attack on any anodic metal connected to it in a couple.

There is little advantage in using stainless steel instead of ordinary steel in relatively stagnant sea water, since fouling takes place and deep pitting results. In rapidly moving sea water, however, fouling does not occur, and aeration is sufficiently strong to maintain the passivating film. Under such conditions, the pitting of stainless steels becomes negligible, while the corrosion rate of mild steel would be increased. For exposure conditions between stagnant sea water and high velocities, the performance of stainless steels varies. Pit-resistant alloys containing molybdenum are superior to other compositions in this exposure range.

The application of stainless steels to shore protection structures does not seem justified. The problems of pitting caused by fouling, intergranular corrosion, stress-corrosion cracking, and galvanic attack of connected metals are serious and inherent to the stainless steels presently available. In addition, the initial cost of stainless steel and the increased difficulty in fabricating it weigh against its use.

Aluminum Alloys

The high standard of performance of aluminum and its alloys in many corrosive atmospheres is attributed to a protective, tightly adhering oxide film on the surface of this metal. This protective film develops almost instantaneously upon contact with oxygen or oxidizing substances in the atmosphere or in many solutions. Aluminum alloys have better mechanical properties than pure aluminum, but as a rule have lower corrosion stability.

Aluminum tends to pit in waters containing chloride ions, particularly at crevices or in stagnant water areas where differential aeration cells cause the passivity to break down. The mechanism of aluminum pitting is analogous to that of stainless steel pitting. Pitting corrosion is more pronounced in the aluminum alloys than in pure aluminum, because the elements used to strengthen the material through alloying generally form second-phase particles in the matrix that are cathodic to the aluminum itself. The oxide film is weak over such cathodic microconstituents, and electrochemical attack of the surrounding aluminum is promoted.

One way of taking advantage of the high strength of an aluminum alloy and the low corrosion rate of pure aluminum is to sandwich the alloy between pure aluminum faces. This aluminum clad material (alclad), metallurgically bonded at the two interfaces, provides cathodic protection to the inner alloy by sacrificial action of the outer layers.

Some aluminum alloys have relatively good corrosion resistance in sea water. The aluminum-manganese alloys are strengthened by a compound that has almost the same electrode potential as aluminum, so that corrosion microcells are not developed. Alloys containing about 5-percent magnesium and aluminum-magnesium-silicon alloys were primarily developed for marine applications. Alloys containing 8- to 12-percent magnesium have a higher mechanical strength. Although the aluminum alloys' corrosion resistance is lower than the 5-percent alloy, the additional strength may justify their use.

Aluminum alloys evaluated in sea water and harbor waters effectively maintained tensile strength over a long exposure period. The alclad alloys and magnesium-containing alloys were the most resistant.

Since reliable corrosion-resistant aluminum alloys can be found for the sea water environment, comparison between these materials and other candidates must be made on the basis of cost and mechanical property parameters. Since aluminum alloys are more costly than structural steels and have lower strength and stiffness characteristics, their applicability is questionable.

Nickel Alloys

Nickel (Ni) and its alloys combine the mechanical characteristics of mild steel with a relatively high degree of corrosion resistance. The major alloys of nickel contain silicon (Si), copper (Cu), chromium (Cr), or molybdenum (Mo), or several of these elements in combination.

The Ni-Cu alloys are the most widely used nickel-base alloys in marine applications. Corrosion rates in slow-moving sea water normally range from 0.2 to 1.0 mpy. Under stagnant water conditions, fouling may occur and induce pitting due to oxygen concentration cells. Tests at Port Hueneme on the Ni-Cu alloy showed an average corrosion rate of 0.5 mpy after 30 months exposure, but pit depths of 10 to 37 mils from marine organisms.

Most of the other nickel-base alloys also have good resistance in flowing water, but tend to pit in quiet or stagnant sea water where marine organisms are attached to the surface. Only one alloy (54% Ni - 16% Mo - 16% Cr) has been found to be resistant to pitting in sea water under all conditions. After 10 years of exposure at Kure Beach, North Carolina, this alloy had a corrosion rate of less than 0.1 mpy and was completely free of pitting.

Although the nickel-base alloys are relatively expensive, their strength and stiffness values (comparable with structural steel) and their corrosion resistance (far superior to the steels) make them interesting alternative materials

for bulkhead construction. Despite high initial cost, use of nickel alloys should be seriously considered when long life is desired and maintenance may be neglected.

Copper Alloys

Pure copper is very useful in stagnant sea water conditions. Its effective corrosion resistance has been proved by its long-time use as sheathing for wooden boats and pilings. The mechanical properties of pure copper, however, make it undesirable for use as a structural material. In addition, pure copper is not satisfactorily resistant to corrosion from rapidly flowing sea water. In turbulent waters, many of the copper alloys are more suitable.

In general, the high-copper alloys have the same order of corrosion resistance as pure copper. The effectiveness of the corrosion resistance depends partly upon the inherent nobility of the base metal and partly upon the ability of the alloys to form protective films of corrosion products. High velocity and turbulent flow of sea water can prevent formation of or remove protective films, thus permitting rapid corrosion. Air bubbles in the sea water have been found to accelerate the effect of turbulence on corrosion.

The common brasses are alloys of copper with 10- to 50-percent zinc (Zn) and often a number of additional elements, such as tin (Sn), iron (Fe), manganese (Mn), aluminum (Al), and lead (Pb). Brass with copper content of about 70 percent (such as Admirality brass) is the most stable of the straight brasses in sea water. If the Cu content is higher, the brass tends to be more susceptible to local attack, particularly at the water line. If the copper content is lower, there is an increased likelihood towards "dezincification," the selective corrosion process in which the metal corrodes as an alloy, with the copper replating on the brass and the zinc forming a corrosion product. The inclination towards dezincification can be reduced by small additions of arsenic, antimony, or phosphorus. The corrosion stability of brass can be increased by addition of aluminum; e.g., a special brass containing aluminum (76% Cu - 22% Zn - 2% Al) is widely used in marine applications.

The aluminum bronzes usually contain not more than 9- to 10-percent aluminum and sometimes small additions of manganese and nickel. In sea water, the aluminum bronzes have higher stability tnan the other copper alloys, with corrosion rates only 1/10 those of copper-tin bronzes and 1/30 these of brasses. Complex alloys of this class are used in the manufacture of ship screws, in which they offer stability against erosion and cavitation.

Copper-nickel alloys containing from 5- to 40-percent nickel have relatively good mechanical properties and excellent resistance to corrosion in sea water. Most attention has been directed to the corrosion-resistance improvement under flow conditions obtained by small additions of iron and manganese.

The most prevalent applications of the copper alloys in sea water environments have been in such places as power-plant tubing on ships. Although corrosion rates can be held to values considerably smaller than those observed in steel structures, this desirable characteristic seems to be outweighed by the lower values of strength and stiffness and the ever-present consideration of increased initial installation cost.

Titanium

This relatively new structural metal has excellent corrosion resistance and a high strength-to-weight ratio. Titanium owes its corrosion resistance to a protective oxide film, which has outstanding resistance to corrosion and pitting in marine environments. It is not antifouling, but there is no pitting or crevice corrosion from fouling organisms.

The high corrosion resistance of titanium is due to the stability of the passive state. In this state, titanium is resistant to oxygen-rich solutions and to solutions containing high concentrations of chloride ions (i.e., it is resistant to stress corrosion cracking in chloride solutions that would produce failure in 18/8 stainless steel in a few hours). The resistance of titanium to corrosion and pitting in both stagnant and moving sea water approaches the resistance of the noble metals. Only very slight uniform loss (0.0001 ipy) occurs over several years of exposure.

The major drawback of titanium metal is the complicated processing necessary to obtain it in a reasonably pure form. Titanium is difficult and expensive to refine because of its high reactivity at elevated temperatures and its relatively high melting point. Although the present cost of this material makes it prohibitive for general use in bulkhead construction, its mechanical properties and corrosion resistance recommend it for use in critical situations.

C. Metallic Coatings

In addition to the use of corrosion-resistant structural metals in the construction of metal bulkheads, it is also possible to use the same corrosion-resistant metals or other metals as thin coatings for the protection of a structural metal in the marine environment.

From a corrosion standpoint, metallic coatings can be divided into two classes: noble and sacrificial. As the name implies, noble metals have better metallic properties (such as corrosion resistance) than the base metals that are below them in the galvanic series (see Figure 4). If a noble metal coating were continuous and nonporous, it would simply isolate the base structural metal from the corrosive environment. All commercially prepared metal coatings are porous to some degree, however, and additional breaks and scratches tend to develop in coatings during handling and use. At exposed pores or scratches in a noble coating, galvanic action occurs in such a way that attack of the base metal is accelerated, and the coating is eventually undermined.

An example of a noble coating on steel is shown in Figure 6, where tin is the protective coating as long as it is continuous. If a scratch breaks the coating, however, the steel becomes the anode in a galvanic cell with the tin and is subject to corrosion in the area of the scratch. The relatively small area of the anodic steel at the scratch must balance the electron flow to a large area of the cathodic tin, so that corrosion is accelerated at the scratch. For noble coatings, therefore, it is important to have a minimum number of scratches or pores, and the pores that exist must be as small as possible so that the access of the sea water to the base metal is minimal. This usually requires increased thickness of coating. Sometimes, the pores are filled with an organic material, or a second metal with a lower melting point is diffused into the coating at an elevated temperature.

For sacrificial coatings, the galvanic cell is reversed, and the base metal is cathodically protected. As long as enough sacrificial material remains on the surface of the structural metal to be protected, corrosion of the base metal does not occur. In this case, the degree of porosity of the coating or the number of scratches in the coating is not of

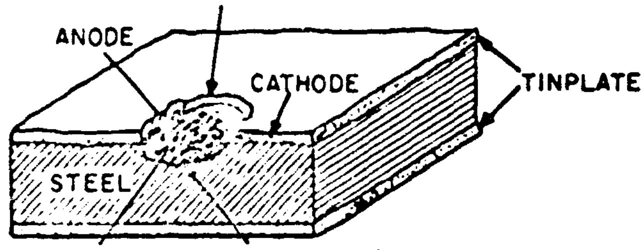


FIGURE 6 - EXAMPLE OF NOBLE COATING ON STEEL-TINPLATE

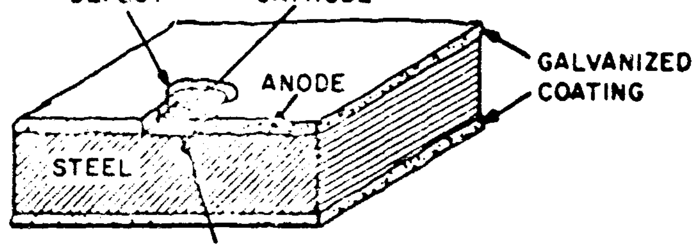


FIGURE 7 - EXAMPLE OF SACRIFICIAL COATING ON STEEL-ZINC

great importance. An example of a sacrificial coating on steel is shown in Figure 7. In the illustration, a zinc coating is applied to form the combination known as galvanized steel. The zinc, which is anodic to steel in the galvanic series (see Figure 4), serves as the anode. The cathodic steel is protected even where it is exposed at a scratch or pore. Since this sacrificial protection lasts only as long as the coating material is present in sufficient quantity to keep the galvanic current flowing in this way, the thickness of the coating determines how long the cathodic protection will continue.

Pretreatment of Surface

Before applying a metallic coating, it is absolutely necessary to remove all scale, rust, and organic matter such as grease. Oxide scale and corrosion products are removed from metals by acid pickling or by mechanical abrasion of the surface. Chemical pickling consists of immersion of the metal in a dilute acid, such as 5- to 10-percent sulfuric acid, until the scale has been loosened or dissolved. Mechanical abrasion methods for descaling include wire brushing, grinding, sand and grit blasting, and polishing. In general, these methods waste metal and produce surfaces somewhat rougher grained than do the pickling methods. Whether the surface should be smooth or rough depends on the nature of the coating and the process by which it is to be applied.

Metal parts that reach the finishing stage are nearly always contaminated with grease, derived either from oils employed for temporary protection or cutting operations, or from lubricating oils and greases from the processing equipment. Grease may be removed by an alkaline bath containing a silicate, phosphate, or aluminate. After this hot degreasing by strongly alkaline solutions, subsequent washing to remove all alkali traces is necessary. A second technique is solvent degreasing, where the metal is dipped into an organic solvent such as naptha. In many cases, it is more efficient to degrease in the solvent vapor, since large amounts of solvent free from grease can be made to condense on the metal. Vapor degreasing involves placing the metal in the upper part of a vessel and boiling solvent in the lower part, so that the liquid condensing on the metal surface drips down, carrying away the grease.

Methods of Application

The process through which a metal coating is applied has a significant influence on the coating's character. Thickness, composition, uniformity, density, continuity, and adherence of the coating are all affected by the application process. The practical parameters of protective quality, appearance, and cost are all related to the method of coating production.

Metallic coatings are applied by hot dipping, electroplating, sintering, vapor deposition, metal spraying, diffusion, and mechanical cladding. Not all metal coatings are readily applied by all methods, but often, two or more processes for a given coating metal and base metal will be equally practical and economical.

One of the oldest commercial processes for applying metallic coatings to other metals is hot-dipping. This process essentially involves immersing the article to be coated in a bath of molten metal for a short time. Little, if any, additional treatment is given to change the properties of the metal coating that adheres to the surface upon removal of the article from the molten metal bath. This method is limited, of course, to coating with metals of relatively low melting point with respect to the melting point or transformation temperature of the base metal.

For a successful coating by the hot-dipping process, it is necessary that the two metals alloy with each other, at least to some extent. As a consequence of this alloying action, which is necessary to produce a uniform and adherent film, the coating is always contaminated with traces of the base metal. The structure of a hot-dipped coating is usually such that there are at least two layers, the inner one called the alloy layer. This inner layer is usually composed of an intermetallic compound of the two constituent metals, which is harder and more brittle than the outer layer of purer coating metal. The brittle character of this alloy layer can lead to undesirable properties in the coated material. The relative thickness of the alloy layer varies with the kind of coating.

Metals may also be coated with another metal by dipping in an aqueous solution of the second metal. Deposits obtained from aqueous solutions are generally very thin, however, and offer little protection against corrosion. Recent electroless methods of dip-coating have been developed to give thicker deposits. The solutions used contain metal salts, a reducing agent, and a catalyst. Nickel-plating has been accomplished by such a process.

Electroplating is perhaps the most important method for the commercial production of protective coatings. The advantages of electroplating over other methods include a more uniform thickness of coating; low-porosity, high-purity coatings without any brittle intermediate layer; the ability to produce a wide range of thicknesses; and the wide range of metals that can be deposited. In the electroplating process, the article to be plated is made the cathode of an electrolytic cell in which a salt of the metal to be plated is present in solution. Since the character of the deposit varies widely with plating conditions, electroplating of metal surfaces is not nearly as simple in actual practice as might be inferred from the simplicity of the principles of electrolytic cell operation. Three interrelated variables must be carefully controlled: chemical composition of the plating solution, temperature of the solution, and cathodic current density. Of the 30 metals that can be electrodeposited, only about 15 are of technical importance. One interesting variable is that composite coatings can be plated as well as single metals.

An important recent development in electroplating is brush-plating, which enables large areas of metal to be plated in situ. A high-current density is used (100 to 500 amps per square dimension), and plating is carried out by moving an anode, which is a tampon or brush carrying the electrolyte, over the metal to be plated.

In the metal-spraying process, the metal in a more or less fluid form is sprayed from a gun onto the base metal in the form of droplets with slightly oxidized surfaces. Any metal that is available in the form of wire and is fusible in the oxyacetylene flame can be sprayed onto a metallic surface. For protective coatings, the major metals used are aluminum and zinc. Metal-spraying is the only feasible

process for the application of heavy aluminum coatings to steel. Ordinarily, there is no alloying action between the coating and base metals. The molten or plastic droplets are flattened into irregular shaped discs as they strike the surface. There is some flow of the coating metal into the pores and irregularities of the surface, so that the coating becomes interlocked mechanically to the surface.

Sprayed metal coatings show a stratification in cross-section, which apparently is an oxidation effect. The density of sprayed metals is less than that of the same metal in cast form because of oxidation and porosity between sprayed particles. The porosity may be reduced by mechanical treatment such as hammering, shot-peening, or wire-brushing. Sealers and topcoats based on vinyl copolymers and vinyl alkyds have been used on sprayed metals. The initial cost of sprayed metal coatings is appreciably greater than for galvanizing, electroplating, or painting, but the possibility of obtaining heavier and more resistant coatings makes this technique particularly attractive for severe exposure conditions. A sprayed aluminum coating of 40 mils thickness on steel has a life expectancy of approximately 12 years in a marine environment. When supplemented with a proper organic coating, only 8 mils of aluminum will protect steel for up to 8 years.

The <u>cementation</u> process of surface treatment involves heating the metal while it is surrounded by another metal, generally in powdered form, to a temperature somewhat below the melting point of the more fusible of the two metals. The characteristic feature of cementation is an appreciable alloying action of the surface layer of the treated metal. The coating produced by this process is simply a surface alloy layer of the base and coating materials. The coating metal as such does not enter into the structure of the coating. As would be expected, the protective quality of cemented coatings against corrosion does not equal that of hot-dipped, sprayed, or electrodeposited finishes. There are cases, however, where the moderate degree of corrosion resistance offered by the application of cementation is sufficient.

Surface alloying by diffusion can also be accomplished through gas-phase deposition. In this process, a halide of the solute metal is passed in vapor form over the surface of the metal to be coated. The base metal is maintained at a temperature at which diffusion takes place readily.

Another process related to cementation is that of attaching sintered carbides to steel surfaces. Such coatings are useful in applications where localized wear and corrosion resistance are required. The carbides of tungsten, tantalum, titanium, cobalt, boron, and silicon are among the most important. The carbides are sintered with a powdered metal such as cobalt or nickel, then brazed onto steel surfaces.

Coatings produced by condensation of metallic vapor may be grouped according to the source of the vapor as follows: decomposition of chemical compounds of metals, cathode sputtering, and evaporation of molten metals. In all three cases, the process involves the use of vacuum equipment and relatively high temperatures. Although these coatings are much costlier than electroplated coatings, it is possible to obtain, by vapor deposition, coatings that cannot be produced in any other way.

Metal cladding, the veneering of base metal plate with other metals, has long been practiced as a coating method The method most used to produce this configuration is roll bonding, in which the coating metal at the desired thickness is rolled onto the base metal at an elevated temperature. Another technique is that of producing a duplex ingot of the two metals, then rolling or drawing the ingot into the desired shape. This process is applicable only for those metals that do not differ radically in their rolling characteristics.

Metallic Coating Materials

The choice of a metallic coating for marine applications is based primarily on the protection it offers against corrosion of the base structural metal. The entire spectrum of metals (listed in the galvanic series in Figure 4) is available, with the type of protection depending upon the relative positions of the base metal and the coating in the galvanic series. Sacrificial coating will result if the coating material is anodic to the base metal, and noble coating will result for coating metals more cathodic than the structural base material. Additional considerations in the selection of a coating for a given base metal in a given environment include resistance to abrasion and feasibility of developing an adequate coating with a reasonably economical process.

The chemical characteristics of the noble metals would seem to recommend them for coatings, but their high cost makes them impractical. In addition, they are so strongly cathodic to such base materials as steel that intensified attack would result at any discontinuity in the coating. Noble metals are readily electrodeposited, and this type of protection may be used for special purposes.

Aluminum coatings on steel are produced mostly by hot-dipping or spraying. Sprayed coatings, usually 3 to 6 mils in thickness, are commonly sealed with organic lacquers or paints. Aluminum in soft waters exhibits a potential that is cathodic to steel and thus acts as a noble coating. In sea water, however, the potential of aluminum becomes more active, and the polarity of the couple reverses, making the aluminum coating sacrificial.

Nickel coatings are generally prepared by electroplating. The nickel coating is either plated directly on steel or over an intermediate layer of copper, employed to obtain a coating of minimum porosity.

Zinc coatings, whether hot-dipped or electroplated, are called galvanized. Hot-dipped coatings are somewhat less ductile than electrodeposited coatings because of the formation of brittle intermetallics in the alloy layer at the coating interface. Zinc coatings are relatively resistant in marine atmospheres, except when sea water spray comes in direct contact with the surface. In sea water, zinc coatings on steel are effective in protecting against the appearance of rust, with each mil of zinc corresponding to about 1 year of life. Since zinc is a sacrificial coating for steel in sea water, lifetime should be directly proportional to thickness of the coating.

Tin plate is usually produced by electrodeposition, since that process leads to more uniform coatings than hot-dipping. Tinned sheet metal can be severely deformed without serious damage to the coating. Tin plate is used in great quantities in the food-handling and -canning industries. Commercial tin plate, in either electrodeposited or hot-dipped form, contains minute pores through which the underlying steel may be corroded at an accelerated rate. Tests conducted in marine atmospheres show severe corrosion of tin plate.

Cadmium coatings are produced almost exclusively by electrodeposition. The difference in potential between cadmium and steel is not as large as the difference between zinc and steel, so that the cathodic protection of steel by a coating of cadmium falls off more rapidly with size of coating defects. Cadmium is more resistant to attack in the marine environment than is zinc, but is more expensive than zinc.

Chemical Conversion Coatings

A coating formed by chemical or electrochemical modification of the metal surface, where the nonreactive coating formed is an integral part of the parent metal, is called a chemical conversion coating. These protective coatings provide an insulating barrier of very low solubility between the metal and its environment. Most of these coatings lend themselves particularly to impregnation with organic coatings, and it is in this application that the chemical conversion coatings presently find their greatest use. In some cases, however, conversion coatings are used without further treatments.

Two techniques are commonly used for forming this type of protective coating: chemical dip, spray, or brush; and electrolytic methods. In chemical dip reactions, an oxide of the base metal or of a metal ion present in the bath is formed on the metal surface. Electrolytic processes depend on an externally applied voltage to promote the formation of protective films in a suitable electrolyte.

Phosphating, an example of the chemical dip process, is generally used to provide a paint base on steel and zinc. For most applications, the phosphate coating is not sufficiently protective without the addition of an organic coating. Another chemical process—chromating—results in enhanced protection of zinc and cadmium in humid atmospheres. These chromate conversion coatings are used purely for protection purposes without additional finishing treatment. Chemical dip methods are also used to develop oxide films on iron, steel, stainless steel, aluminum, and copper and its alloys. The resulting chemical oxide coatings on stainless steel, aluminum, and copper provide relatively good resistance to corrosion, but in the other cases, their protective value is limited.

The foremost application of the electrolytic process is in the anodizing of aluminum alloys. The anodic oxidation of aluminum and its alloys produces a surface coating with relatively high resistance to corrosion and abrasion. Of the common electrolytes used in anodizing, chromic acid produces the most corrosion-resistant coatings on a given alloy. Sealing this coating with hot water or an alkali dichromate improves its protective value.

Additional discussions on coatings for the protection of the structural element of a bulkhead follow in later sections. Organic and inorganic nonmetallic coatings are discussed in Section IV under "Coatings for Maintenance." Application of all kinds of coatings under in situ conditions is discussed in Section V under "Coatings for Repair."

D. Concrete

Concrete that is properly proportioned, mixed, and placed is one of the most durable materials available for shore protection. Service records indicate that quality concrete can endure for 50 years with only modest maintenance requirements.

Cast-In-Place Concrete

The traditional construction technique for concrete structures, including sea walls, is to build forms at the on-site location and cast the concrete to its final form in its service position. Forms are stripped off after a suitable curing period and can be reused in an adjacent location. A technique often used to construct long concrete structures in segments is stage construction of alternate blocks. This type of construction typically would be employed in massive gravity sea walls requiring several vertical lifts as well as longitudinal separation into blocks.

Since the procedure of forming for cast-in-place concrete and removing the forms after the curing period does not allow efficient reuse of forms, techniques have been developed for their faster reuse. In slip forming, the forms are moved along the wall construction site a segment at a time as soon as the concrete in one segment has cured sufficiently to retain its shape. The project should be programmed in sections so that the slip-form system can be translated as rapidly as possible.

An even more recent development has been the concept of extrusion of concrete shapes in a continuous strip of a given cross-section. This technique employs a moving placing machine much like a highway pavement spreader. The exit chute has the shape of the finished cross-section and a stiff, fast-setting concrete mix is compressed into the exit form against the back pressure from the portion just placed. This extrusion technique has been successfully used for continuous curbs and medial barriers on highways, and is being experimented with for low walls. It is doubtful whether such a technique for placing concrete could be employed for high walls of considerable bulk or for walls in deep water.

A typical cross-section of a cast-in-place concrete gravity sea wall is shown in Figure 8. A second typical sea wall, shown in Figure 9, is supported on piles rather than on a continuous spread footing. This stepped-wall design breaks the force of a wave into increments and, therefore, can be of lighter construction than the type which receives the full force of a wave at one time. Sheet-piling is used at the toe of this latter sea wall to prevent undermining by wave action. A rule-of-thumb developed from model studies is that the depletion of the beach reaches to a level of about one wave height below mean low water. The sheet pile protection, therefore, should penetrate to below that level.

Precast Concrete

To avoid the problems of on-site forming and placement of concrete in difficult environments, the technique of precasting concrete at an off-site location has been adopted. Shaped concrete blocks are precast in a convenient size, placed in position, and grouted together through a key arrangement to provide a continuous structure. The accurate quality control of concrete mixes possible when precasting leads to high durability and ultimate economy in construction.

The technique of precasting can be applied to any shape of concrete wall or bulkhead, as long as care is taken in grouting the sections together and adequate foundations are provided. Even a bulk gravity sea wall could be precast in blocks small enough to be handled by a crane. A precast wall could be fabricated on a grid of precast concrete piles jetted into place.

The most promising development in concrete construction within the recent past is that of prestressing of precast concrete members. Concrete is 8 to 10 times as strong in compression as in tension. When it is designed for a flexural application in which both tensile and compressive stresses will be present, some provision must be made to improve its tensile behavior in order to use its compressive capability effectively. In conventional reinforced concrete, steel bars are added to tensile zones to carry the tensile loads. Prestressing offers an alternative to this conventional approach. Before the precast member is subjected to

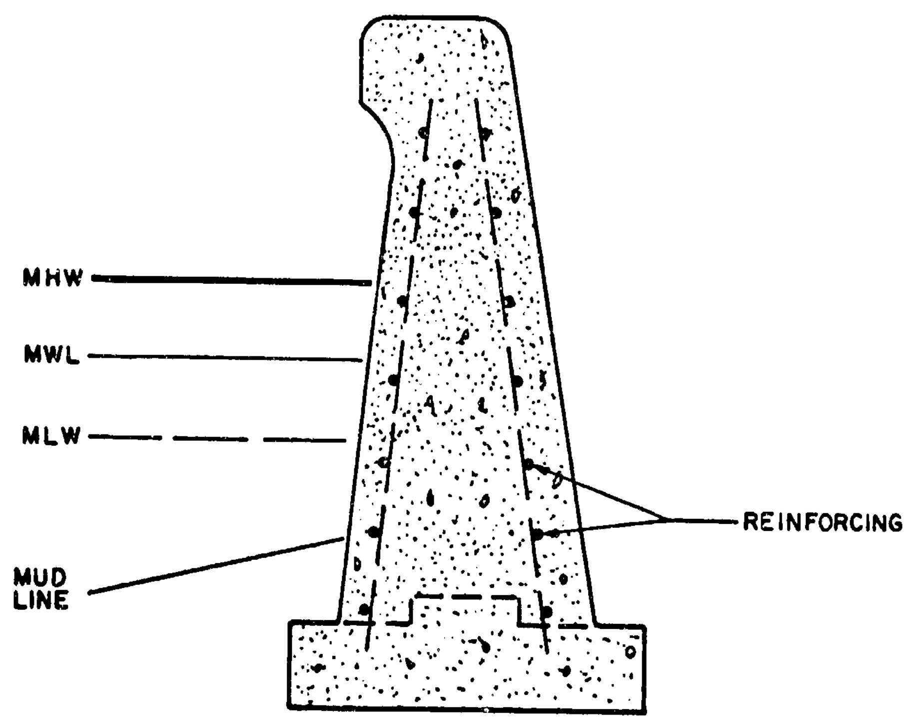


FIGURE 8 — SECTION OF TYPICAL CAST CONCRFTE SEA WALL

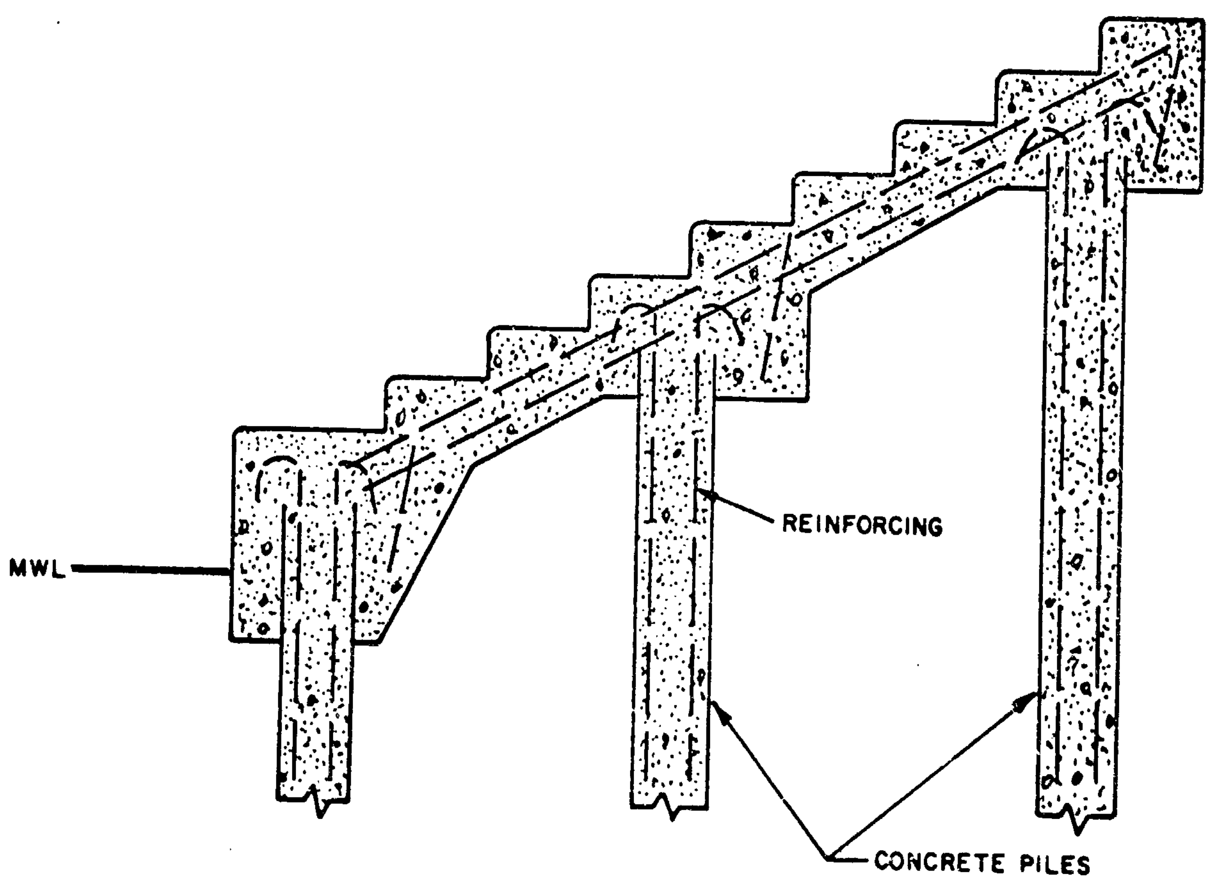


FIGURE 9 — SECTION OF TYPICAL STEPPED CONCRETE SEA WALL

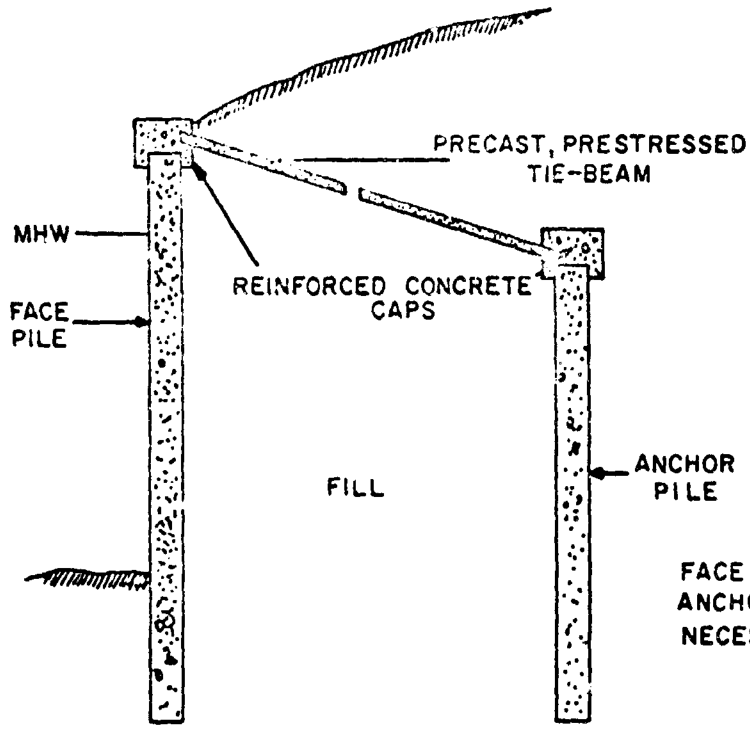
its service loading, the portion which is to carry the tensile load is prestressed into compression through the use of prestressing cables. This compressive stress must then be overcome in service before the member will be subjected to a tensile stress; thus, its actual capacity to carry an imposed services load has been enhanced.

Prestressing of precast units such as sheet piles and tie-beams permits the use of thinner, lighter weight members, thereby reducing material, fabrication, and handling costs. For sheet pile construction, prestressed concrete is such an improvement over reinforced concrete that it has practically replaced it. In a typical bulkhead employing prestressed concrete, a face wall of concrete sheet piles is capped with reinforced concrete and tied back with a system of precast, prestressed tie-beams to an anchorage system of concrete deadmen or piles. A typical installation of this type is shown in Figure 10. Many bulkheads of this type, with clear heights of up to 18 feet, have been constructed.

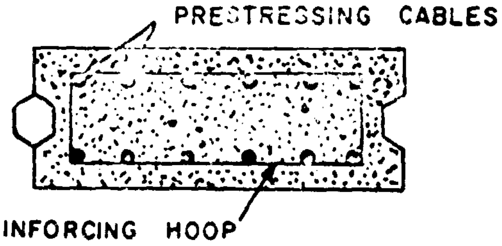
Design of these walls is largely a matter of experience and judgment. One guideline used is that the minimum penetration in good material should be 0.6 times the height of the wall above grade. The groove on one side of each pile section is matched by a tongue in the lower portion of the adjacent pile, and by a groove from a point 3 or 4 feet below the water line to the top. The recess formed by these matching grooves is filled with grout after driving, making a joint relatively impervious to the wave action. The foot of each pile is beveled on one side so that the tip will be forced against the adjacent pile during installation.

Many prestressed sheet piles are constructed with the prestress reinforcing symmetrical to the front and back faces. This concentric prestress, approximately 700 psi, provides a member that can be safely hauled, handled, and placed without cracking. The efficiency of sheet pile in bending can be substantially increased by using eccentric prestressing, as long as moment reversal does not occur over the length of the pile.

Wall designs for greater water depths might include a continuous wale at some distance below the top of the wall



FACE PILING CONTINUOUS, ANCHOR PILING SPACED AS NECESSARY.



SECTION OF PRESTRESSED
CONCRETE PILE

FIGURE 10-TYPICAL PRESTRESSED CONCRETE
SHEET PILE WALL

for tie-back connections, as shown in Figure 11. Larger prestressed piles can be cast with interior voids to reduce their weight.

Concrete sheet piles are placed by a variety of methods, depending upon the character of the material on the location site. In granular soils, they generally can be jetted to grade. In less easily eroded soils, they are driven with steam or gravity hammers on driving blocks. In very dense material, prepunching may be required.

Design for Durability

Concrete exposed to sea water may be attacked by chemicals in the water. It also is subjected to considerable pounding by wave action, and between high and low water it is subjected to a continual wetting and drying action. The principal cause of deterioration, however, probably is corrosion of the reinforcement, which expands and disrupts the concrete.

When certain precautions are taken in the design, mixing, and placing of the concrete, it should resist the sea water environment almost indefinitely. The best protection is to have the concrete strong, hard, dense, and impermeable. Specific recommendations for durable concrete in sea water environments are as follows:

- The aggregate should be sound and well-graded, with a maximum size determined by using the following three criteria: no stone larger than 1 1/2 inches, no stone larger than 1/6 the smallest dimension of the forms, or no stone larger than 3/4 the minimum reinforcing bar spacing.

- The water/cement ratio should be kept low, not exceeding 0.56 to 0.60, including water entering the mix as free moisture on the aggregate.

- Reinforcements and all other permanently imbedded metal parts should have a minimum cover of 3 inches, with 4 inches cover at corners.

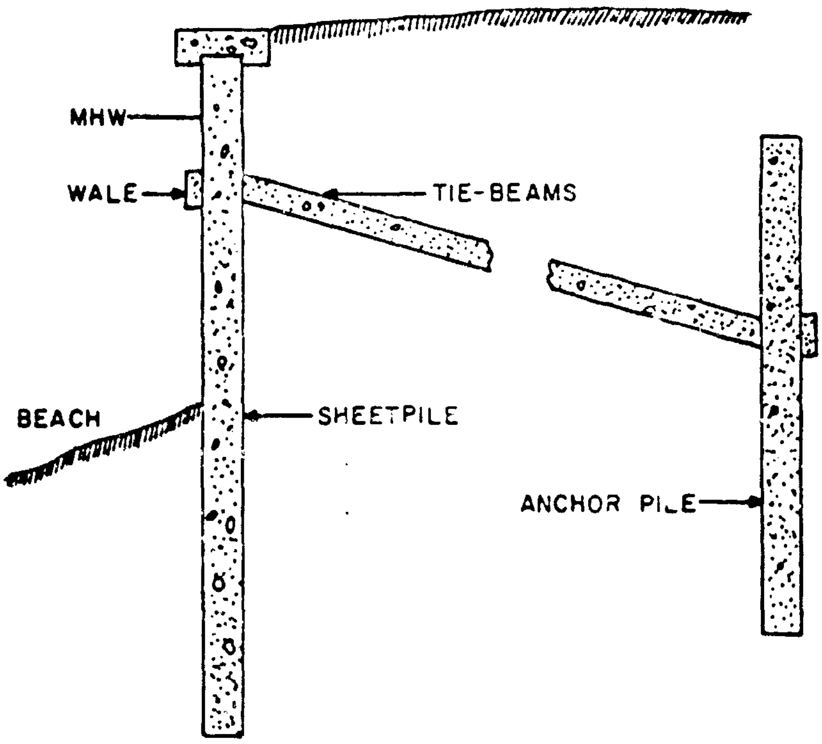


FIGURE II — SECTION OF TYPICAL PRESTRESSED CONCRETE SEA WALL

- Air-entrained concrete should be used to protect from freeze-thaw damage and to aid in workability.

- Placement of concrete in the forms must be done carefully to prevent segregation. Within the tidal zone the concrete should be placed continuously to avoid construction joints.

- After placing, the concrete should be protected from the sea water for at least 4 days and should be kept moist for several days at a temperature above 50° F.

- Cement used for making concrete exposed to sea water should have low alumina and lime content.

In addition to mix and placement variables, there are certain surface treatments which increase the resistance of concrete to aggressive agents. Many such treatments produce only a shallow surface effect and are suitable only for improving the resistance of concrete to the less aggressive agents. Such surface treatments include:

- two coats of magnesium or zinc fluosilicate;

- two coats of sodium silicate or water glass;

- two or three coats of boiled linseed oil (applied hot); and

- two or three coats of natural or synthetic resin.

For highly aggressive solutions, the concrete must be physically prevented from coming in contact with the solution. Treatments for this type of exposure include:

- two coats of bitumen or coal tar;

- application of bituminous mastic or asphalt; and

- acid or alkali-resisting bricks or tile laid in special mortar to form a completely impervious lining.

These surface treatments for concrete are necessary only in excessively aggressive environments. The strong, hard, dense, and impervious concrete described above is sufficiently durable for normal sea water exposure.

E. Timber

Timber selected for use in shore protection structures must meet three types of criteria:

- adequate structural properties when damp or wet;
- availability in appropriate sizes and lengths at reasonable costs; and
- resistance to deterioration in the shore environment.

Allowable design stresses for timber in various moisture conditions are available in Federal Government and lumber industry publications. Since timber strength is reduced at high moisture content, allowable design stresses are generally less than half those for dried lumber. Strengths of typical firs and pines currently used in timber shore construction are about 1/10 those of structural steels, and moduli are less than 1,000,000 psi. This means that timber structures for the same loading situation would be considerably more massive than steel structures. Since the sizes and lengths of structural timber members are limited by nature, the dimensions and load capacities of shore structures built of timber are similarly limited.

The principal problem to be considered in connection with timber shore structures is that of deterioration in the marine environment. Damage by marine boring organisms to timber in sea water occurs throughout the world. The rapidity of the attack depends upon local conditions and the kinds of borers present. Current practice indicates that all timber installed in a marine environment should be pressure treated with a preservative before installation. If the treatment is thorough and penetration deep enough, several preservatives have been found to be effective in preventing borer attack.

An alternative to using preservative-treated native softwoods for timber shore structures is to use tropical woods. These are more dense, strong, stiff, and resistant to marine environment than our native woods. Although

specific tropical woods are resistant to certain marine borers, no single wood has been found that is resistant to all biological attack. Disadvantages in the use of these tropical woods include difficulty of fabrication, expense (about twice the cost of native timbers), a tendency to undergo deterioration due to surface checking when in service, and an inability to pressure-treat the wood effectively with preservatives. Since the tropical timbers are more expensive than fully treated native woods, their use is only justified in specific critical installations.

Configurations

Timber has been used in several configurations for shore protection facilities such as bulkheads and walls. A typical timber bulkhead arrangement is shown in Figure 12. This configuration is similar to those used when sheet-steel piling or prestressed concrete sheet piles are used in anchored bulkheads, but it is limited to lower heights by the size limitations and lower design stresses of timber.

Filled timber cribs, such as the one shown in Figure 13, were used extensively in earlier bulkhead construction. The top of the timber crib is usually terminated at a low water level and the wall above built of concrete. Firm foundations are required for this type of construction; improper foundations often lead to excessive settlement under the heavy crib construction.

Plywood has been developed to deal with the anisotrophy and size limitations of natural wood. Marine-grade plywood, bonded with non-water-soluble adhesives, is available which withstands immersion in water. Pressure preservative treatments are now in use to impregnate plywood through its entire thickness in sheets up to 1 inch thick. Plywood sections thick enough and large enough for major bulkhead installations, however, are not readily available at this time.

One configuration employed to protect structural timber from marine environmental attack is that of sheathing each member with a protective layer. A hardwood timber which will not readily accept preservatives may be sheathed with a sapwood layer that is easily impregnated. In addition, a layer

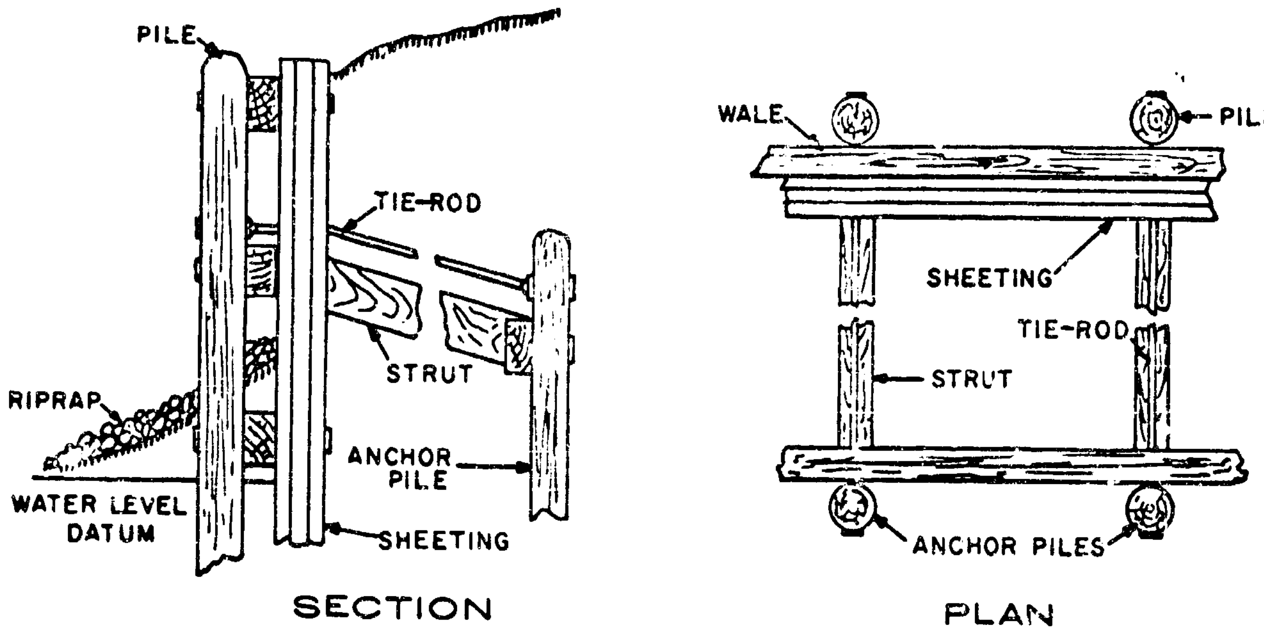


FIGURE 12 – TYPICAL TIMBER BULKHEAD

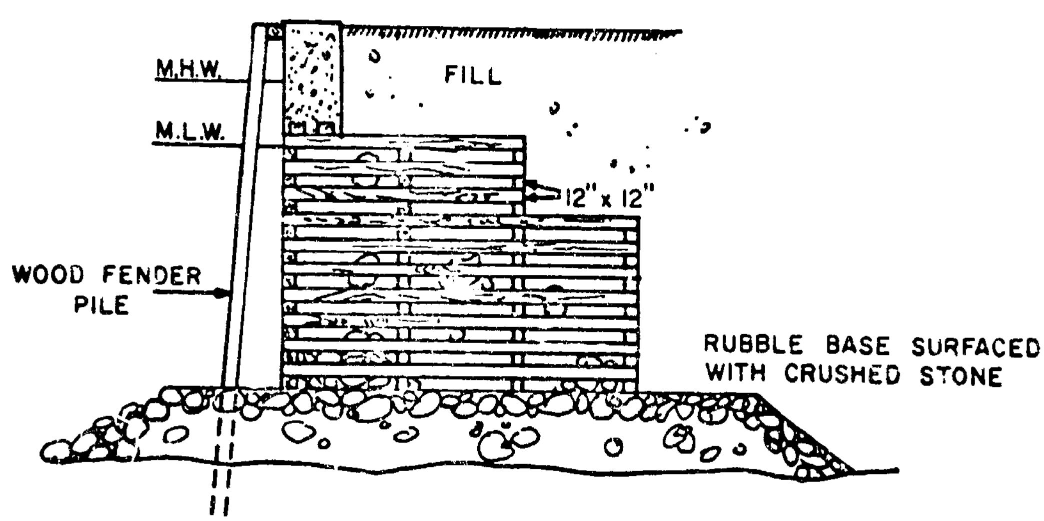


FIGURE 13 – TYPICAL TIMBER CRIB WALL

of asphaltic felt is used between the sheathing and the structural timber to further protect against borer intrusion. Sheathing can be replaced periodically, if required. Structural timbers can also be sheathed with a thin layer of metal, such as copper or aluminum, which acts as a barrier between the marine environment and the timber.

Timber which is properly pressure-treated with a preservative can be made resistant to marine borers in their underwater environment. This does not prevent decay due to fungus attack in portions of the structure above the water line, however. This relative deterioration has led to the development of so-called "composite construction," in which treated timber is used below the water line and a more resistant material, such as concrete, is used above the water line. Thus, timber is used underwater where placement of concrete is difficult and expensive and concrete is used above the water line where it is not subject to the decay of timber.

Wood Preservation

Preservatives used for timber may be classified into two main groups: oils and oil-borne preservatives and water-borne preservatives. In the first group are the by-product preservative oils in general use: coal-tar creosotes, the creosote-coal-tar solutions, and the creosote-petroleum solutions. Coal-tar creosote is a distillate of coal tar produced by high temperature carbonization of bituminous coal. The practice of mixing coal tar with coal-tar creosote has become common for the treatment of timbers. Coal tar is too viscous and insoluble to penetrate wood well, but its use in combination with coal-tar creosote serves to reduce the cost of the preservative and to decrease the tendency of the treated wood to check or split in service. Petroleum oils are also used as diluents for coal-tar creosote. When injected into timbers, creosote-petroleum solutions reduce checking to a greater degree than straight creosote.

Many oil-soluble chemicals have high toxicity to wood-destroying organisms, but are too costly or unsuited

physically for use alone as wood preservatives. Pentachlorophenol and copper napthenate are two commonly used oil-borne preservatives.

Water is used as a solvent for wood preservatives because of its cheapness and availability. Water-borne preservatives afford little protection to timbers subject to wet environments, however, because of their solubility in water. Most preservatives of this kind are subject to leaching from the treated wood whenever it is in contact with water or with wet soil. Some newer water-borne preservatives are designed to form compounds of low water solubility as the water evaporates from the treated wood. When this is accomplished, the resistance of the preservative to leaching can be very high. Preservatives of this type generally contain salts of two or more of the following elements: copper, zinc, chromium, and arsenic. Copperized chromated zinc chloride (CCZC) is an example of such a leaching-resistant, water-borne preservative.

Many preservatives of all types are considered proprietary in that they are patented or sold under trade names. The number of such proprietary preservatives on the market is great and constantly changing. An analysis of wood preservatives, indicating which compounds are effective, has been made by the American Wood Preserver's Association.

The selection of the proper method of treatment is as important as the selection of the proper preservative. Pressure processes are generally used to permit maximum penetration of the preservative. Two basic methods are employed in injecting the preservative into the wood: the full-cell process and the empty-cell process. Treatment by the full-cell technique leaves the cells of the wood full of preservative, within the depth of penetration. The empty-cell process leaves the cell walls saturated, but no free liquid in the cell cavities. The full-cell process is generally used in treating material to be used in marine construction.

A relatively new process in which a combination of preservatives is used seems to hold the best promise for timber preservation in marine environments. A double treatment combines an initial copper salt injection with a final

creosote pressure treatment. It appears that the copper salt penetrates the cell walls, strengthening and hardening them; then the later creosote treatment fills the cell cavities. The full-cell protection of the creosote thus prevents the copper-salt preservative from being leached away. Early results from test specimens indicate extremely good resistance to borer attack in timber treated with this double process.

Use of Timber for Shore Protection

Preservation-treated timber has been used extensively in the past for piling, docks, and other waterfront structures. However, these gradually have been replaced with stronger and more permanent types of construction. This change has occurred because of the great advances made in reinforced and prestressed concrete design and in the greater use of steel piling. Also, the necessity of designing larger and stronger structures has led to the use of materials other than wood. Wood is still one of the cheapest, most flexible materials available for small shore facilities, but its lack of permanency in comparison to metals and concrete is limiting.

F. Other Materials

Natural Materials

Sea walls can be constructed of natural materials such as sand, soil, or stone. These materials can be stabilized beyond their natural resistance to erosion through the addition of a cementing medium in the surface layers.

Stone, in the form of block walls or rip-rap, has long been used in shore protection. Block walls are normally constructed of massive elements whose stability against wave action is assured, but the blocks may also be bonded together by an intermediate layer of mortar. Rip-rap is normally graded through its cross-section, so that the outer surface has elements large enough to be stable in wave motion, while the inner material is fine enough to act as a filter against loss of shore material. In both block stone and rip-rap installations, an adequate foundation must be prepared to accept the heavy wall. The outward toe of the stone or rip-rap wall must be buried below the level of bottom material affected by wave action, perhaps one normal wave height in depth. Either stone blocks or rip-rap can be used as protective cover for earth embankment walls rather than as a structure wall per se.

Soil or sand can be used to form sea walls if adequately protected by stone cover or by cement or chemical stabilization. Soil-cement protection consists of soil, portland cement, and water which have been proportioned, mixed, placed, and compacted so that a dense, uniform material results. The principal criterion for selecting appropriate soil is gradation, with the ideal being coarse, sandy, or gravelly soils containing about 10- to 25-percent of material able to pass a No. 200 sieve. Soil-cement slope protection has been successfully achieved by means of both central-plant and mixed-in-place procedures. The protecting material is placed through a mechanical spreader and compacted by means of heavy rollers.

Asbestos-Cement Bulkhead Sheets

Corrugated asbestos-cement sheet materials are composed of a combination of graded long asbestos fibers and special

types of portland cement. The types of portland cement used have high sea water and sulfate resistance; coating the fibers with this cement gives a strong, lightweight material. The coated fibers are aligned in a co-planar position in the sheet during formation. The rapid high-pressure expulsion of water in the hydraulic forming process results in a prestressed sheet. This slight compressive prestress, plus the geometry of the corrugations, provides maximum resistance to bending. Corrugated asbestos-cement bulkhead sheets are jetted into place, then capped with a reinforced concrete cap which is in turn anchored back to a deadman with steel bars. Present asbestos-cement sheets are of such limited thickness and length that they cannot be used safely for shore lines facing the open sea where wave action could be substantial. For low-rise bulkheads in sheltered locations, however, even the present materials provide corrosion-resistant, economical installations.

Modular Brick or Block Panels

Standard masonry construction could be used for sea walls, but the standard mortar would crack and lose strength in the marine atmosphere. A recent development in mortars is a latex additive that imparts fast set, low shrinkage, early strength, and strength retention after curing to the mixture. This latex-additive mortar is presently being used to prefabricate brick panels at ground level and then grout them in place. This development may have a possible application in sea wall construction. Although regular cement and concrete lose strength when placed in water after having been cured in relatively dry conditions, the latex-additive mortar retains its original strength under these conditions. A sea wall built of masonry units would have the advantages of modular construction, i.e., special bricks could be used in the high wear zones and replacement of damaged or worn portions of the wall would be relatively easy.

IV. MAINTENANCE MATERIALS AND TECHNIQUES

Sea water is a corrosive medium, and its corrosive effectiveness may be enhanced by local additions of contaminants or biological agents. Tidal action causes alternate wetting and drying that is detrimental to certain materials from which the bulkheads may be constructed. Splash from wave action can be damaging since the combination of moisture with oxygen enhances corrosion. The rate of corrosion is also affected by the temperature and relative acidity of the sea water. The increased oxygen content in the water near the surface, developed through wave action, results in the formation of an electrolytic cell, which accelerates corrosion a small distance below the water level in metal bulkheads. The portion of the bulkhead near the sea bottom is subjected to erosion as solid matter is transported along its length. The design of the bulkhead, including the selection of materials for its construction, must minimize the detrimental effects of this hostile environment.

In addition to careful design and selection of materials in the initial installation of a bulkhead, maintenance is desirable to retard deterioration. Maintenance refers to that continual or periodic activity applied to keep the bulkhead from deteriorating in its service environment, or to slow its rate of deterioration. The following sections describe the major maintenance techniques and materials available for application to steel bulkheads in marine environments.

A. Cathodic Protection

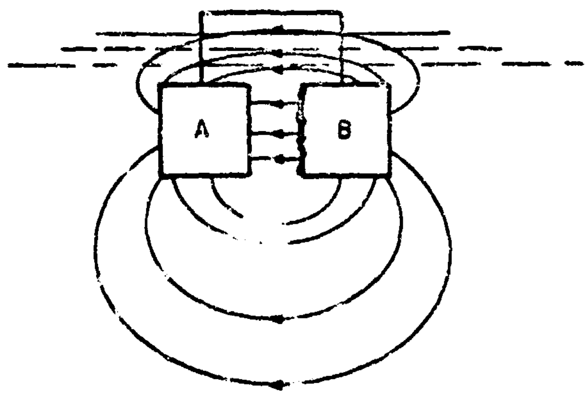
Corrosion of metal bulkheads in aqueous environments is primarily electrochemical in nature and is due to a current passing from anodic areas of the metal into the electrolyte and returning to the metal at cathodic areas. This type of corrosion can be largely overcome by impressing a countercurrent on the metal in an amount sufficient to neutralize the naturally developed electric currents. Cathodic protection serves this preventive maintenance function.

Cathodic protection was introduced in 1824 by Sir Humphrey Davy, who used zinc in the control of corrosion on war ships. Since that time zinc has been traditionally used to protect the hulls and shafts of steel ships in the vicinity of bronze propellers. Today, cathodic protection is used for the protection of both active and inactive naval vessels, underground pipelines and tanks, and steel structures in contact with sea water. Cathodic protection can be applied to protect such metals as steel, copper, lead, brass, and aluminum against corrosion in practically all acqueous media, including most soil conditions and sea water. However, it cannot be used to prevent corrosion above the water line, because the impressed current cannot reach the areas of a metal that are out of contact with the electrolyte; i.e., sea water. Thus, in the case of sheet-steel piling in sea water, cathodic protection could be used effectively to reduce the corrosion rate in the oxygen concentration cell area below the water surface, but would not be useful in the splash zone above the water surface.

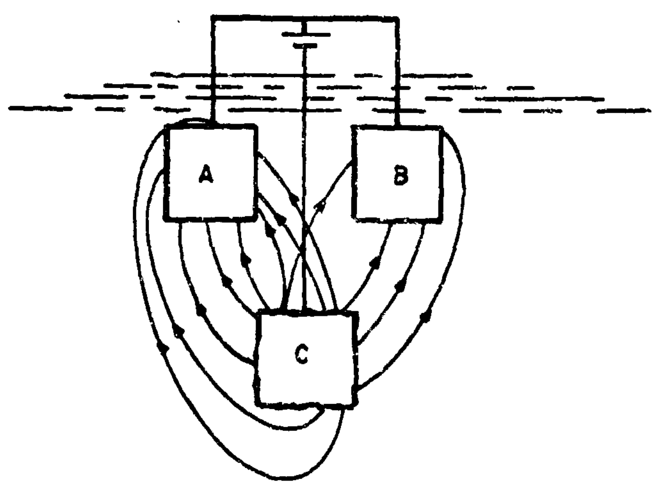
Principles of Operation

When two dissimilar metals are electrically connected and immersed in an electrolyte, there is a current flow through the electrolyte and metals in such a way that anions enter the solution from the anode and at the same time electrons move from the anode to the cathode through the metallic connection. The rate of corrosion at the anode depends on the amount of current flowing, which is determined by the potentials and resistances in the circuit. This basic corrosion cell is shown in Figure 14A, where Plates A and B may be dissimilar metals or may be the same metal in different conditions, such as in an oxygen concentration cell.

If another electrolytic cell is established where a third metallic plate (C) and a source of electrical potential are added to the circuit, the flow of electrical current can be modified. As shown in Figure 14B, the positive pole of the potential source is connected to C, and the negative pole to B. Then, B will be made more negative by electrons flowing to it, and since these electrons will reduce the tendency for positive ions to go into solution, the corrosion rate at B will be reduced.



14 A



14B

FIGURE 14— SCHEMATIC DIAGRAM OF CATHODIC PROTECTION

The following three phenomena, operative in cathodic protection, cause reduction of corrosion:

- The potential of the metal is lowered so that the formation of metallic ions going into the solution in the electrolyte is prevented.

- The electrolyte near the surface of the metal becomes more alkaline because of the reduction of oxygen or hydrogen ions, and for ferrous metals, this decrease in acidity will cause inhibition of corrosion.

- The increase in alkalinity will cause the precipitation of insoluble salts, which may deposit on the metal and produce a protective calcareous scale.

In sea water, there are enough dissolved mineral ions to deposit, by electrolysis, a layer of calcareous or siliceous material on the metal being protected by cathodic protection. Such a layer can seal the surface of the metal in a way similar to the action of paint. The resistance of the electrical circuit increases as the layer forms, and the current is automatically decreased if the voltage applied is maintained at a constant value. This protective layer is continually being redissolved, but is deposited at a higher rate by maintenance of the protective current. Protection from corrosion is maintained by the mineral layer for a considerable period of time, even when the protective current stops.

The electrical potential needed for cathodic protection may be provided by a metal that is more electronegative than the metal to be protected (sacrificial protection) or by an external potential source and an auxiliary anode (impressed current protection). These two alternative means of supplying cathodic protection, shown schematically in Figures 15A and 15B, are discussed in detail below.

<u>Sacrificial Protection</u>

If the auxiliary anode consists of a metal more active in the galvanic series (see Figure 4) than the metal to be

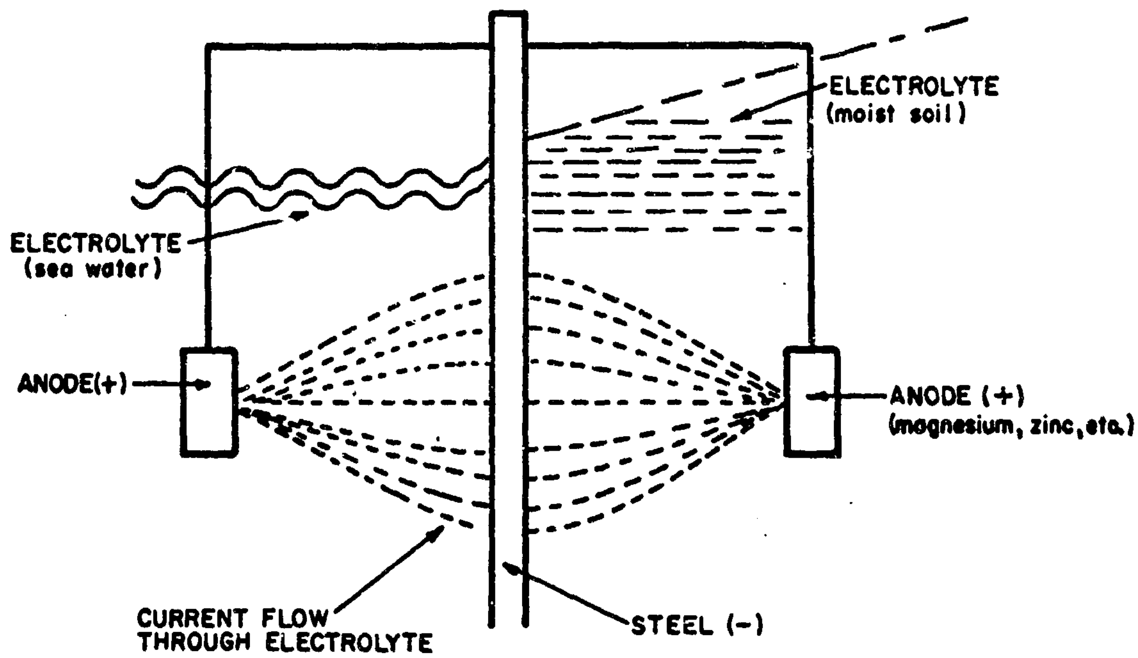


FIGURE 15A — CATHODIC PROTECTION USING SACRIFICIAL ANODE

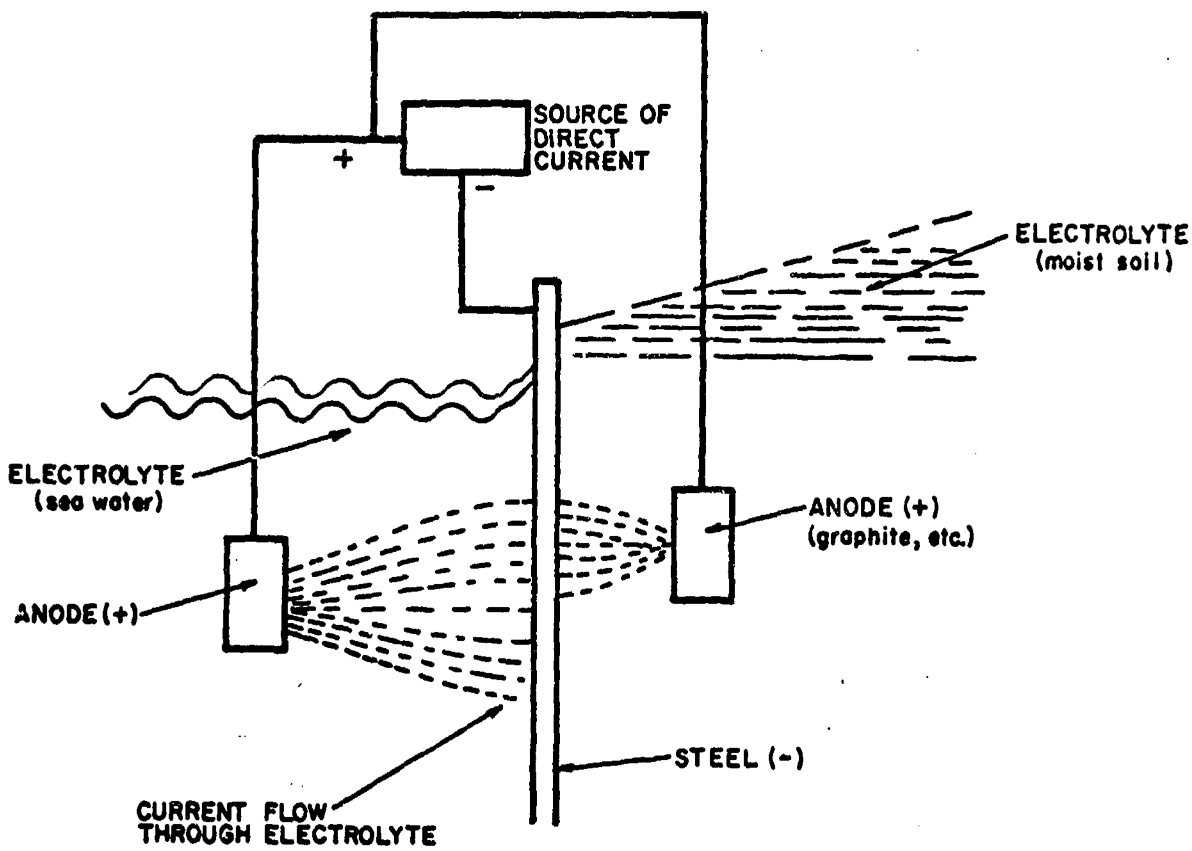


FIGURE 15B— CATHODIC PROTECTION USING IMPRESSED CURRENT METHOD

protected, a galvanic cell is set up in which the auxiliary anode makes all parts of the metal to be protected cathodic. The earliest experiments on cathodic protection were performed with zinc anodes that were electrically connected to copper plates and immersed in sea water. In the galvanic cell formed in this way, the zinc was the anode and corroded, while the copper was the cathode. When sufficient current flowed, the copper became cathodically protected. The zinc corroded to provide the necessary current and, thus, was called a sacrificial anode. This method of obtaining cathodic protection can be used with other combinations of metals as long as the electrical parameters are such that sufficient current can be generated to bring about the desired cathodic protection. Faraday, for example, showed that when zinc and steel were in electrical contact in sea water, the steel did not corrode.

Sacrificial metals used for cathodic protection are magnesium, zinc, aluminum, and alloys of these three metals. Magnesium is most widely used because its high current yield gives maximum current distribution. The addition of aluminum to magnesium reduces self-corrosion, but minor alloying elements such as copper, nickel, and iron can significantly increase the self-corrosion and thus decrease the efficiency of magnesium as a sacrificial anode. In zinc anodes, impurities must be restricted to very low limits to avoid the formation of insulating films which may rapidly reduce current output. Iron impurities are particularly harmful, and should be limited to 0.0015 percent maximum. Zinc of 99.99 percent purity is recommended for use as sacrifical anodes. Since pure aluminum develops an oxide film which inhibits its activity as an anode, it is necessary to alloy the aluminum to maintain an effectively high potential. Alloys suitable for anodes include an aluminum/zinc alloy which acts as a low driving voltage anode and an aluminum/tin alloy which acts as a medium driving voltage anode.

Sacrificial anodes serve essentially as sources of portable electrical energy. They are particularly useful when electric power is not readily or economically available. The potential differences between sacrificial anodes and protected cathodes are generally low, so that only limited dimensions of structure can be protected by each anode This

low voltage is sometimes an advantage over impressed voltages, however, in that the dangers of overprotection of some portions of the system and of stray-current damage to adjoining metal structures are reduced.

Sacrificial anodes are usually cast, and are available in a great range of shapes and sizes, from 5 to 200 pounds. Current output is related to composition, surface area and shape, while the lifetime of the anode depends on the ratio of surface area to weight and the current demands of the particular installation. With these factors in mind, an anode can be designed so that the initial current yield is high to assist in polarization, while it later falls off to that required to maintain polarization. Such high initial output can be achieved, for example, by the use of finned anodes. When the fins have wasted away, the resultant fall in output current leads to a decreased rate of anode consumption. The rate of consumption of magnesium alloy anodes is about 17 to 20 pounds per ampere year. A 50-pound magnesium anode for sea water use might typically be designed for a 2-year lifetime.

The advantages and disadvantages of the sacrificial anode system of cathodic protection can be summarized as follows:

- Advantages:
  - Sacrificial anode protection can be used where there is no available power source.
  - No initial investment in power equipment is required.
  - The system is relatively foolproof, and requires little supervision (e.g., current cannot be applied in the wrong direction, thus producing corrosion rather than protection);
  - Installation is simple.
  - The anode leads are cathodically protected.

- Disadvantages:

  - The current available depends on anode area, which may have to be substantial for large structures.

  - The cost of the electrical energy produced is considerably higher than for generator produced energy.

  - For large structures, the high current flow requires large size leads to keep resistance losses low.

Impressed Current Protection

This type of cathodic protection requires an external source of direct current and an auxiliary electrode located some distance away from the structure to be protected. The direct current source is arranged with its positive terminal connected to the auxiliary electrode, and its negative terminal connected to the structure to be protected. Then, the current flows from the electrode through the electrolyte to the structure.

While sacrificial anodes were limited by their driving voltage and had to be engineered to suit this limitation, impressed current engineering is freed of this limitation. The applied voltage is not critical, but need only be sufficient to supply an adequate current density to all parts of the protected structure. To protect a large structure with sacrificial anodes, a large number of anodes would be distributed along the structure, involving considerable installation work. With impressed current protection, such a structure could be protected with a much smaller number of anodes, each fed with a greater current.

The source of current is usually a rectifier supplying low-voltage direct current of several amperes. Motor generators have been used to transform alternating current to the required direct current, but maintenance has proven to be troublesome. Windmill generators have been used in areas with

dependable prevailing winds.

If a structure is protected with a small number of electrodes, certain parts of the structure may be overprotected in achieving the complete protection of all other parts. Moderate overprotection of steel structures usually does no harm, except for some waste of electric power and increased consumption of auxiliary anodes. In extreme cases of overprotection of steel, however, additional disadvantages can result if hydrogen is generated at the protected structure in large amounts. Such excessive hydrogen generation can cause blistering of organic coatings, and hydrogen embrittlement of the steel.

Control of the cathodic protection current can be achieved simply by varying the output from the direct current source. Thus, the output of the cathodic protection system can be balanced to that required by the structure, a technique which cannot readily be applied with sacrificial anodes. At the time of initial installation, adjustment of individual anode outputs can be made to balance the protection. Subsequently, the entire cathodic protection network can be adjusted to meet the demand. This dynamic control of the system can be operated either manually or automatically.

Since the current is being supplied from an external source, the anode material used in impressed current systems requires different properties than those of the sacrificial metals. The resistance of the anode must not change greatly either by consumption or by polarization. The anode system should be relatively permanent, having a low overall life cost. The cost of the anode will depend upon required lifetime, the most economical driving voltage, and the possibility and ease of anode replacement.

The pioneers of impressed current cathodic protection used scrap iron and steel as consumable electrodes. Such anodes have been particularly successful in sea water, where the degree of polarization is small. Pure aluminum has also been used successfully as a consumable electrode in sea water. Usually, however, where economic advantage leads to the selection of an impressed current system rather than sacrificial

anode protection, the most economical impressed current electrode will be a permanent anode.

The first permanent anodes were made from graphite and carbon. Graphite costs more than scrap iron, both initially and in subsequent higher electrical power costs. It is also more fragile than scrap iron, so must be installed with greater care. However, graphite anodes are consumed at about one-tenth the rate for scrap iron. Silicon-iron anodes, containing 14% Si and 3% Mo, are also used as permanent electrodes for impressed current protection. They can be used at higher current densities than carbon, while having a comparable economic life. Silicon-iron anodes have been used extensively in marine cathodic protection installations in the past, but are being largely superseded by platinized titanium. In the latter arrangement, a thin film of platinum is plated onto a titanium support. Platinum, with a 10-percent addition of rhodium or palladium, is a truly permanent anode in sea water. Titanium is heavily anodized in most electrolytes and becomes self-insulating through the formation of a film. This film prevents further corrosion so that when the platinum cladding acts as an anode, the titanium carrier remains an insulated support. Since the layer of platinum on the anode needs to be only a few microns thick, this arrangement is much more economical than the use of solid platinum anodes.

Cathodic protection rectifiers are generally oil-immersed to provide long, trouble-free service. Air-cooled units are less expensive on initial installation, however, and may be used if adequate maintenance is available. The rectifiers, which are usually selenium or silicon types, are mounted on poles or other suitable platforms.

For sacrificial anodes where the connection cable is cathodically protected, cable insulation is not important. For impressed current systems, however, high quality insulated cable is required. Polyethylene-insulated PVC sheathed cables have been found generally suitable for this purpose.

The amount of current required to protect a surface depends upon coatings used, the nature of the electrolyte, and the amount of oxygen concentration. The applied current density must always exceed the current density equivalent to

the measured corrosion rate in the same environment. Thus, the greater the potential corrosion rate, the higher must be the impressed current density for protection. If the protective current induces precipitation of an inorganic scale on the cathode surface, the total required current falls off as the scale builds up. The precise requirements for current density for complete cathodic protection can best be determined by potential measurements taken directly at the protected structure in its service environment. Approximate values of current requirements for steel in sea water are 3 to 5 milliamperes (ma.) per square foot for painted steel, 10 ma. for bare steel, and 20 to 150 ma. in high velocity, oxygen-rich water.

The advantages and disadvantages of impressed current cathodic protection systems may be summarized as follows:

- Advantages:
  - the protecting current can be varied to any desirable amount to optimize operation as a function of time; and
  - leads need not be large, since resistance losses can be overcome by increasing applied voltage.
- Disadvantages:
  - continuous direct current electrical power must be available;
  - more technical supervision is required (e.g., connections must be made so that the current flows in the right direction); and
  - the anode leads must be well insulated and waterproofed in order to avoid their preferential consumption.

The general dividing line between sacrificial and impressed current systems for cathodic protection appears to

be the size of the installation. Sacrificial anodes are impractical for a large installation because of the number of anodes required, and the frequency with which they must be replaced. Conversely, impressed current systems are impractical for small structures because of high installation costs. For the normal sheet-steel piling installation, then, an impressed current system would be indicated.

Application to Sheet-Steel Piling

The sheet-steel piling used in wharf and bulkhead construction can be cathodically protected against corrosion by impressed current techniques. Since the piling is usually corrugated or otherwise offset periodically, the area of the metal to be protected is greater than the frontal area. In addition to the current density required to protect the seaward side of the piling, a lesser amount will be used to protect the side which is adjacent to the backfill soil. If the piling had been treated with a bituminous paint coating before driving, the structure might require 1 to 2 ma. per square foot for protection on the sea water side and an additional ½ to 1 ma. on the land side. In this situation, 100 yards of piling 40 feet deep would require a current of about 36 amps. The steady-state current demand could be reduced by an initial polarization, say 150 amps for ten days, bringing a reduction of 50 to 70 percent in the current required to maintain protection on the sea water side. Since the polarization treatment would not be as effective on the land side, the overall current density requirement might be reduced by 40 to 50 percent of the nonpolarized requirements.

In many cathodically protected structures, particularly those in high-resistivity soils, calculations are made for potential spread so that anodes may be appropriately positioned. When the electrolyte is sea water or a similar low-resistance electrolyte, however, the location of anodes is of secondary importance.

Combined Use With Coatings

It is common practice to use an insulating coating on structures in conjunction with the application of cathodic protection using either impressed current or sacrificial

anodes. In cases where the distribution of current is not ideal, various coatings may be used to redistribute the current selectively. The insulating coating need not be pore-free, since the protective current flows preferentially to exposed metal areas.

The principal value of coatings on cathodically protected structures is to interpose electrical resistance between the electrolyte and the metal, and to keep the metal dry. A strongly adherent coating of high resistance will prevent corrosion by suppressing the corrosion currents. Resistance of new coatings can range from a few thousand to several million ohms per square foot. A coating that admits water will not maintain high resistance. The principal value of cathodic protection with a good coating is to prevent corrosion and pitting at the breaks in the coating. Since less current flows in a coated system, the cost of electrical energy is decreased.

Stray Currents and Interference

Stray currents may be produced during the operation of cathodic protection, and may traverse buried pipes or cables or other structures which are not being cathodically protected. This stray current interference can accelerate the corrosion on such nearby metallic structures. There are two mechanisms by which such corrosion occurs: the current may flow in the metal, causing it to have various potentials, or it may flow in the electrolyte, thus developing a potential gradient. In either case, a variation in potential will cause an electrolytic cell to be formed.

Economic Considerations

The guarantee of corrosion control makes it possible to specify thinner sections, avoiding any extra thickness as a safety factor against corrosion. This saving alone can pay for a major part of the capital equipment and installation costs of cathodic protection.

Corrosion costs can be estimated and comparisons can be drawn to economically evaluate protection. Where the methods of protecting the metals are more expensive than

the detrimental effects of corrosion, then protection cannot be justified. In situations where replacement of the metal component requires dismantling of additional superstructures or the necessity of periodic shutdowns for repairs, it is more economical to use preventive protection.

Use of coating in conjunction with cathodic protection must similarly be justified on economic grounds. The cost of the coating must be balanced against the reduced cost of the cathodic protection in the electrolytic zone. Various combinations of coatings and required amounts of cathodic protection current can be compared to determine the optimum protection arrangement with respect to cost over the lifetime of the installation.

B. <u>Coatings for Maintenance</u>

Metal coatings were discussed previously in the section concerned with initial installation techniques. Since it is assumed that the organic coatings are less permanent and would have to be periodically maintained during the lifetime of the protected structure, the discussion of this type of coating has been included with maintenance techniques.

<u>Application Conditions</u>

Whenever possible, organic coating application should be carried out under dry conditions. Surface preparation should be carried out in a manner similar to that described above for metallic coatings, so that all rust, mill scale, grease, and dirt are removed. After preparation of the surface, it is left in a condition highly susceptible to corrosion, so that application of the coating should follow immediately.

It is poor practice to apply organic coatings to surfaces covered with a film of moisture. Such a film affects adhesion and can reduce the lifetime of the coating. Since moisture also prolongs drying time, dust and dirt can become attached to the coated surface. In marine environments, these difficulties are increased by the saline atmosphere. Salts trapped beneath a coating lead to the rapid formation of voluminous rust, which forces the coating outwards and finally disrupts it.

<u>Organic Coatings</u>

To protect against corrosion, a good organic coating should:

- provide a good vapor barrier, as impermeable as possible to water and oxygen;
- inhibit corrosion, so that any water reaching the metal surface has less effect; and
- provide long life at low cost.

In paints, the first criterion is met by application of multiple coats, each of which seals up pores and other defects in previous layers. The diffusion path through the paint film is also increased by incorporating pigments, particularly those having the shape of flakes, oriented parallel to the metal surface. The second criterion can be met by incorporating, into the prime coat, pigments that are effective corrosion inhibitors when dissolved in water. The third criterion must be measured in terms of performance in the service environment. Both material cost and labor must be considered in evaluating the cost-lifetime relationship.

Paints

A paint is basically an insoluble pigment dispersed in an organic fluid medium. The organic medium is modified by dryers and thinners, which are volatile compounds added to control viscosity during manufacture and application. Before a paint is formulated, it is necessary to know the circumstances under which it will be applied and the subsequent exposure conditions. These conditions and the properties required in service will dictate the choice of binding medium, which, in turn, will limit the choice of solvents. The quantity of solvent used will depend on the intrinsic viscosity of the binder and the paint viscosity appropriate to the method of application (brushing, spraying, or dipping).

Since a single paint rarely has all of the required properties, a system of paints is normally used. A paint system usually consists of a primer, undercoats, and a final coat. The primer is selected for adhesion and protection of the metal substrate. Undercoats normally have a high pigment content for barrier formation and a low gloss. The final coat is chosen for protection and finish. In marine applications where marine organisms may grow on painted surfaces, an additional coat of an antifouling paint is applied.

The most important component of a paint is the binding medium or vehicle, which determines the physical and chemical properties of the paint. The general characteristics of various binding media follow:

- Drying oils. On exposure to the air, these oils oxidize and polymerize to solids. Linseed oil is the most important of the drying oils and is the only one commonly used in its natural state. Its main use is in corrosion-inhibiting primers. Paints based on raw linseed oil have the disadvantages of slow drying, lack of gloss, and insufficient flow to level out brush marks. Improvement of the properties of the raw drying oil results from one of three kinds of heat treatment: boiled oils (heated with a dryer), stand oils (heated with the exclusion of air to bring about a degree of polymerization), and blown oils (heated without a dryer but with air blown through to produce a material rich in hydroxyl polar groups).

- Oil varnishes. All varnishes and paint media prepared from drying oils and natural or synthetic resins are classified as oil varnishes. The introduction of such resins as rosin, gum congo, rosin-modified phenolics, and oil-soluble 100-percent phenolics results in improved drying and film properties. Oil varnishes can perform excellently as primers for clean or pretreated ferrous metal surfaces. However, they do not have as much tolerance for wire-brushed rusted surfaces as do oil-based primes.

- Alkyd resins. These polyesters of moderate molecular weight are perhaps more widely used than any other type of binder. The diverse members of this family can be divided according to their use: air drying (alkyds capable of air drying do so through oxidation of the drying oils they contain), stoving (based on drying or semi-drying oils, where the oxidative properties are of less importance), and plasticizing (those alkyds used in conjunction with a larger percentage of harder resin).

- *Amino resins*. The two amino resins in common use, urea formaldehyde and melamine formaldehyde, are used as components in stoving finishes.

- *Epoxide resins*. These are made up of long chain building blocks with hydroxyl and epoxide groups available for reacting with other compounds. Paints based on this type of reaction may be supplied in two containers to be mixed immediately before use. If the combination of compounds is non-reactive at room temperature, stoving is employed for curing. Epoxide resin complexes have outstanding chemical resistance.

- *Polyurethanes*. These resins, like the epoxides, also have excellent chemical resistance. Air-curing types are supplied in two-pack containers, and one-pack types are available for stoving.

- *Vinyl resins*. These resins are prepared by polymerization of compounds containing vinyl groups. The most widely used in paint manufacture are copolymers of vinyl acetate (giving solubility in volatile solvents) and vinyl chloride (giving chemical resistance). This group of resins air-dries solely by solvent evaporation, and they remain permanently solvent soluble. Many members of this group have poor adhesion to metal, but good adhesion is obtainable after initial application of an etching primer.

- *Chlorinated rubber*. This binder is soluble in aromatic solvents, and paints made from it dry by solvent evaporation alone. Chlorinated rubber, plasticized to reduce its brittleness, has good resistance to a wide range of chemicals and to water.

- **Nitrocellulose.** Paints based on this binder are important in the protection of metals because of a combination of quick drying and excellent durability. Nitrocellulose alone will not give a continuous coating, and must be mixed with other components (plasticizer and hardening resin).

The function of the pigment in a paint varies, depending on the application. In a finish coat, the function is to provide color, but in a primer coat, it should contribute to preservation of the metal substrate and to enhancement of the adhesion of the paint system. Pigments are essentially dry powders, insoluble in the paint medium and dispersed by a grinding technique. Materials used as pigments vary from naturally occurring minerals to man-made organic color pigments. They may be divided into priming pigments (red lead, calcium plumbate, zinc chromate, zinc powder), color pigments (red oxides, titanium dioxide) and extenders (asbestin, barytes, china clay, silica). Red lead is widely used in primers for steel work, but is likely to accelerate the corrosion of non-ferrous metals. Calcium plumbate is unique in its adhesion to newly galvanized surfaces, but is less effective than red lead on steel. Zinc chromate, used for both ferrous and non-ferrous metals, is the inhibitive constituent of each primer. Zinc powder is able to protect steel cathodically, provided that about 95 percent by weight of zinc is present. Flake pigments such as aluminium and micaceous iron oxide do not have inhibiting properties but are able to decrease the permeability of the paint, and consequently contribute to better protection.

A paint rarely consists solely of pigment dispersed in a binder. Small quantities of additives, dryers and thinners, are usually included. The dryers are used in all air-drying and many stoving paints containing drying oils. They are organic salts of metals such as cobalt, lead, and managenese. Thinners may be used to reduce cost or to obtain a higher solids content at a given viscosity. In addition, anti-oxidants may be employed to prevent skinning in containers, and surface-active agents may be used to facilitate the dispersion of the pigments.

The conversion of liquid paint to a dry film may involve a variety of chemical reactions, or merely the escape of a volatile solvent. In either case, the dry film will consist of relatively large polymer molecules. On metallic substrates the polymer molecules are oriented to some degree, and the polarity that leads to this orientation affects the strength of the adhesion of the film to the metal surface. The dry paint film can affect the electrochemical corrosion reaction by inhibiting the cathodic or anodic reaction or by providing a high resistance path between the anode and cathode.

The choice of paints for marine use depends upon the conditions of service. Paints used above the waterline do not differ fundamentally from those used on inland structures. Paints used for underwater protection of steel encounter more stringent conditions, however. The corrosion of iron immersed in sea water with an ample supply of dissolved oxygen proceeds by an electrochemical reaction in which caustic soda is produced at the cathode. Therefore, paints used on steel immersed in sea water must resist alkaline conditions. In addition, the paint films should have high electrical resistance in order to impede the flow of corrosion currents between the metal and the water. The paints used for structural steel ashore, including red lead in linseed oil, do not meet these requirements. Suitable priming paints should be based on phenolic media, pitches, bitumens, chlorinated rubber, and vinyls.

Ordinary paints with a simple linseed-oil vehicle are not suitable for structures immersed in water; they would last less than one year. Better protection of up to several years is obtained from a multi-coat system of synthetic vehicle paint. Since the synthetic vehicle system, such as epoxy resin paint, is quite expensive, other alternatives are used to produce thick, long-lasting organic coatings for immersion in sea water. Thermoplastics and bitumens will now be considered for anti-corrosive coating use.

<u>Plastic Coatings</u>

The use of plastics for corrosion resistant coatings is a new and expanding field. Whereas the maximum thickness of

paint films rarely exceeds 0.01 inch, coatings of thermoplastics can be applied in much greater thicknesses. Application by dipping or spraying is very rapid. These coatings have good anti-corrosive properties, good adhesion, high abrasion resistance, and an attractive appearance. At present, there are six plastics used commercially to provide such coatings:

- plasticized polyvinylchloride (high resilience, corrosion resistance, and electrical insulation);

- penton, a chlorinated polyether (hard, reasonably non-brittle, anti-corrosive);

- nylon (low water absorption, excellent oil and solvent resistance, hard);

- cellulose acetate butyrate (high gloss, relatively poor adhesion, and corrosion resistance);

- polyethylene (good adhension to substrate metals, relatively good corrosion resistance, tough high-density grades);

- polytetrafluoroethylene and polytrifluoromonochlorethylene. (Polytetrafluoroethylene is largely used as an antistick or low-friction surface coating.) Polytrifluoromonochlorethylene is the best of the anticorrosive coatings, where cost is of secondary importance. A completely nonporous coating of polytrifluoromonochlorethylene can be applied at between 0.006 and 0.012 inches, depending on the substrate metal.

The use of plastics as heavy protective coatings continues to grow at a rapid rate. Their use permits simultaneous advantage to be taken of the mechanical strength of metal and the corrosion resistance of plastics. One problem which must be kept in mind is the difference between the coefficients of thermal expansion of the coating and the substrate. This problem can be largely overcome by annealing

the composite member after the hot spraying or dipping operation to produce a relatively stress-free coating at service temperatures.

Bituminous Coatings

Bituminous coatings are used extensively in marine conditions. Bitumen and asphalt are amorphous solid or semi-solid substances which are essentially hydrocarbons. They are found naturally in several locations, and can be produced artificially as residues in the distillation of crude petroleum. Bituminous coatings also include coal, tar, and pitch, which are the residues from the carbonization of coal. These coatings may be applied hot or cold, depending on their formulation. The protection obtained depends on thickness of the coating, with thicknesses approaching 0.25 inches required to get a coating free of pinholes with a thick hot coal-tar coating.

A great variety of asphalts and pitches are used in solution rather than as hot melts. The bitumens may be used alone in volatile solvents or in combination with drying oils, resins, mineral fillers, and pigments. Bituminous emulsions containing 40- to 50-percent asphalt dispersed in water provide relatively thick coatings for metal protection.

Perhaps the most popular coating today for steel piling in marine environments is coal-tar epoxy. This coating is a combination of coal, tar, pitch, and epoxy resin. It is formulated to take advantage of the resistance to mineral acids, low water absorption, surface wetting, and adhension of the pitch, and the chemical and abrasion resistance and hardness of the epoxy. Coal-tar epoxy coatings are generally sprayed on in two or more applications, with a minimum thickness of 16 mils specified. This type of treatment can protect a sheet-steel piling in sea water for up to seven years before any alternative measures such as recoating or installation of cathodic protection become necessary.

Anti-Fouling Coatings

The finishing paints for underwater protection of metals should be anti-fouling, designed to prevent the attachment of

marine growth. These paints contain chemicals poisonous to t larvae-setting stage of marine plants and animals and s wly release them into the sea water to maintain a thin layer in which larvae cannot survive. The poisons usually used are compounds of copper and mercury. Anti-fouling compositions have a limited lifetime before the poison-release rate falls below that necessary to prevent settlement of marine organisms. Typical useful lifetimes are one to three years.

Inorganic Coatings

Several non-metallic inorganic coatings are used to coat metal components for corrosion protection. Included in this category are vitreous enamels, ceramics, portland cement, concrete, and cementiferous paints. Vitreous enamels, glass linings, and porcelain enamels are all essentially glass coatings of suitable coefficient of expansion fused on metals. Enamelled steels exposed to the atmosphere last many years. Failure eventually occurs by crazing of the coating, which allows rusting to take place.

The development of ceramic coatings has been stimulated by the need for temperature-resistant materials for aerospace applications. Their use has been extended to the protection of industrial and commercial high temperature equipment. Ceramic coatings, which like porcelain enamels are vitreous in character, have shown good resistance to corrosion and erosion in elevated temperature applications.

Portland cement and concrete coatings have been used effectively for many years to protect water pipes. Portland cement coatings are low in cost and have a coefficient of expansion near that of steel. They are easily applied and repaired by trowelling, casting, or spraying. Thicknesses for neat cement coatings range from .25 inches to more than 1 inch, where the thicker coatings must be reinforced with wire mesh. Portland cement coatings are used to protect pipe on both the water and soil sides and are also used to protect metals against sea water. For large-diameter water pipes and other metal structures, heavier coatings of concrete are used. The disadvantages of cement

and concrete coatings lie in their sensitivity to damage by mechanical or thermal shock.

One of the difficulties of paint application on marine structures is that it often must be carried out under humid or wet conditions. This difficulty may be overcome by the use of paint formulations based on inorganic media, called cementiferous paints. The media employed for such paints include sodium, lead, and ethyl silicates, oxychloride cements, phosphates, and butyl titanate. The pigment used is usually zinc. These paints are resistant to water and organic solvents, but are not resistant to strong acid or alkali because of the high zinc content. While it is necessary in organic media to have sufficient zinc to give metallic contact between the particles and the base metal, this does not apply for inorganic media which react with the zinc, making it chemically part of the coating.

Tests on Coatings

The search for economical, effective coatings for steel structures subjected to marine environments has led several agencies to conduct comprehensive tests of different coatings in actual sea water locations. The U.S. Naval Civil Engineering Laboratory at Port Hueneme, California, for example, has conducted extensive tests on protective coatings for steel piling in a marine environment. Observations were made after exposure periods of six, twelve, eighteen, twenty-four, and thirty months. Ratings were assigned to each coating system based on ASTM photographic reference standards: a rating of ten indicates an intact film and no rusting, and at the other end of the scale, a rating of zero indicates that a coating has lost all protective properties. The results of tests on the eight most promising coatings in the series of tests are shown in Figure 16. Note that more than half of these coatings, which had been prescreened from an original group of twenty-three coatings, failed completely in one zone of attack or another during the thirty-month duration of the tests. This would indicate that any coating considered for a large-scale installation should be carefully tested in that environment first. It would also indicate that there is a need for more development

SYSTEM	NUMBER OF COATS	THICKNESS (mils)	TOTAL THICKNESS (mils)	Exposure Period (Months)	Ratings: Splash Zone	Ratings: Tidal Zone: Upper 3 ft. of Tidal Zone	Ratings: Tidal Zone: Next 3 ft. of Tidal Zone Extending to Mud Line	Ratings: Embedded Zone
Vinyls				12	9	9+	6	9
Aluminum vinyl	-	-	-	18	9	9	5	9
MIL-C-15328 (Formula 117), wash prime	1	0.5	-	24	9	9	3	9
MIL-C-15929A (Formula 119), vinyl red-lead primer	4	4.0	-	30	9	9	1	9
Aluminum-pigmented vinyl finish	2	1.5	6.0					
Vinyl mastic	-	-	-	12	9	9+	9	9
Vinyl-phenolic primer	2	2.0	-	18	9	9	8	9
Vinyl mastic finish	2	10.0	12.0	24	9	9	7	9
				30	9	9	7	9
Saran	-	-	-	12	9	10	7	9
Saran (Formula 113/49)	6	6.0	6.0	18	9	9+	5	9
				24	9	9+	4	9
				30	9	9+	3	9
Metallized				12	9	10	9	10
Flame-sprayed zinc wire	1	5.0	5.0	19	8	9	9	9+
				24	7	9	8	9+
				30	6	9	8	9+
Coal Tar				12	9	8	9	9+
Cold-applied coal tar	-	-	-	18	9	6	6	9
MIL-C-18480, coal tar coating	3	19.5	-	24	9	[illegible]	3	9
MIL-C-15203, bituminous emulsion	3	12.0	31.5	30	9	4	1	9
Asphalt				12	9	8	7	9+
Mica-filled asphalt emulsion	..	-	-	19	9	7	4	9+
MIL-C-15328 (Formula 117), wash primer	1	0.5	-	24	9	6	2	9+
JAN-P-735 (Formula 84), alkyd zinc chromate primer	1	1.0	-	30	9	5	1	9+
Mica-filled asphalt emulsion finish	6	28.0	39.5					
Synthetic Rubber:				12	9	10	9+	9+
Neoprene bushing composition	-	-	-	18	9	9	9	9
Neoprene primer	.	1.5	-	24	9	8	8	9
Catalyzed neoprene finish	3	19.0	20.5	30	9	8	8	9
Phenolic				12	9	10	7	9+
Phenolic mastic	-	-	-	18	9	9+	7	9+
Catalyzed phenolic mastic primer	1	10.5	-	24	9	9+	5	9+
Catalyzed phenolic mastic finish coat	1	9.0	19.5	30	9	9+	4	9+

FIGURE 16 — RESULTS OF TESTS ON COATING SYSTEMS

of coatings with relatively long protective life at reasonably economical costs.

In Situ Application

For coatings to be used as a maintenance technique for bulkheads, they must be capable of being applied in situ after the initial coating has lost its effectiveness. Since the useful lifetime of presently available coatings is in the range of two to seven years, it is apparent that such in situ application is much more important than initial application. Painting or otherwise coating a structure above the water line is relatively straightforward as long as deposited salts and corrosion products are removed and application to a clean, dry surface is possible. Below the water line, however, coating is difficult.

One system which has been shown to be somewhat effective for in situ underwater application is a two-pack epoxy coating. Heavy epoxy coatings can be applied by forming or hand lay-up techniques. The cured coating can be expected to protect the base metal against corrosion for several additional years. To date, such applications have been made only to surfaces cleaned down to bare white metal. Costs have been in the $5 per square-foot range. While this magnitude of cost might be justified on H-piling, where each member may carry a concentrated load from an expensive superstructure, it is economically questionable for sheet-steel piling installations.

Another approach to coating underwater areas is local dewatering. A box containing equipment is placed with its open side against the surface to be coated. The box is sealed to the surface with rubber gaskets and is then dewatered. The coating is applied by the equipment in the box, which is activated and fed from outside the dewatered zone.

In addition to the possible use of organic and inorganic coatings to recoat underwater areas, in situ metal coatings should be considered. As discussed above in the section on metal coatings, metal spraying and in situ electroplating can be field-applied.

V. REPAIR TECHNIQUES AND MATERIALS

If a sheet-steel bulkhead installation has not been regularly maintained by such techniques as cathodic protection and periodic recoating, progressive deterioration will occur. Sheet-steel piling structures suffer progressive deterioriation as a result of several influences:

- Corrosion from the sea water causes loss of metal in the splash zone and in the active electrolytic zone a short distance below the water line. Perforation through gross loss of metal or wear can then lead to loss of fill material from behind the bulkhead.

- Mechanical abrasion caused by the impact of wave-carried material and by scouring at the toe of the wall also contribute to the progressive deterioration on the sea side of the bulkheads. Similar effects on the shore side of the structure can also lead to deterioration.

- Progressive changes in alignment can result from poor anchoring support, irregular soil characteristics, or tie-rod failure.

- Corrosion due to ground water movements or stray currents can cause perforation of the sheet steel from the back side.

Two methods of correcting the deterioration of sheet-steel bulkheads, by replacement with new installations and by preventive maintenance techniques, have been considered in detail in earlier sections of this report. Techniques for the repair of badly deteriorated steel bulkheads are considered in this section.

Once significant rusting or erosion has occurred, repair techniques must be employed to return the structure to its design condition or to arrest further deterioration. Corrective measures taken may vary considerably in complexity, depending upon the desired lifetime and cost parameters.

A well-conceived repair technique should also attempt to prevent or retard the renewal of the corrosion cycle. Several of the repair techniques considered here can bring the bulkhead back to its original functional condition and strengthen the structure against the corrosive environment.

A. <u>Welded Reinforcement</u>

Steel members that have corroded only in limited areas may be repaired by welding steel reinforcing plates onto the structure. This repair technique is particularly applicable to steel H-piling, where severe corrosion is generally limited to a small zone near the mean water level. Fish plates welded onto the flanges and webs can transmit the total column load from solid steel above the corroded zone to solid steel well below the water line.

Holes in sheet-steel piling are not as easily repaired by welding techniques. Local holes can be repaired by welding on plates or sections of sheet-steel piling, but a number of such holes along the length of a bulkhead would make the cost prohibitive. Perforation might occur, for example, in each web of a Z-piling wall. To patch such holes, plates would have to be carried to solid steel well above and below the accelerated corrosion zones, and would have to be welded to the heavy interlock sections. Such a repair system would be very expensive on a badly deteriorated sheet-steel bulkhead.

Deterioration of tie-rods will cause the upper portion of a bulkhead to bow outward. When one tie-rod fails, additional stress is placed upon adjacent tie-rods, and progressive failure is likely to occur. When local changes in wall alignment are noticed, the tie-rods should be checked quickly to determine if tie-rod failure is causing the problem. The most severe corrosion of tie-rods usually occurs at the end adjacent to the sheet piling, while the section of the rods toward the anchor end may be in good condition. Repair usually involves excavation to expose the tie-rods and turnbuckles; new sections of rod are then spliced in to replace the corroded section. Splice rods are generally used to reinforce the butt-welded joints.

B. Concrete Techniques

If a deteriorated sheet-steel bulkhead still has adequate strength to support the applied loads below some section, concrete encasement down to that section can be used to prevent further deterioration and to seal perforated areas against loss of fill. This technique is applicable to corroded H-piling sections, where the concrete is used to transmit column stresses, as well as to sheet-steel bulkheads.

Depending upon the relative severity of attack on the inside and outside faces of a sheet-steel piling wall, encasement may be extended to cover both faces. Although protection of both faces is expensive, because of additional excavation and material costs, beneficial protection can be derived if the encasement is carried down far enough to include the wales and tie-rod ends. Since corrosion rates generally fall off rapidly below the active electrolytic zone in sheet-steel piling, the concrete encasement needs to be carried down only a few feet below the mean low water level. If abrasion or corrosion of the balance of the submerged sheet piling is unusually severe, the concrete encasement can be extended to the mud line. If the lower end of the encasement form is submerged but does not reach the mud line, a counterweight outrigger beam can be used to support the form. Encasement techniques were used at NAS(NY) and will be discussed in Sections VIII and IX.

Concrete may also be used to repair sheet-steel bulkhead deterioration by spot patching. If concrete plugs are used to seal perforations in the sheet-steel bulkhead, loss of fill material will be stopped. To place a concrete patch so that it is supported behind the bulkhead wall at the edge of the perforation, a cavity must be prepared or provision must be made to place the concrete under pressure or impact in order to displace the fill material. Since ground water is likely to be flowing through the perforation from behind the wall, neither of these techniques is easy. Corrosion deterioration will continue on adjacent areas of the steel piling, and spot patching has limited effectiveness as a repair technique unless it is applied each time a new perforation appears.

A third possibility for the use of concrete to stabilize deteriorated bulkhead walls is that of grouting the fill material behind the wall to make it self-supporting. This alternative would not prevent further deterioration of the bulkhead, but would simply use the bulkhead as a form for the pressure-grouting operation. The possibility of using a pressure-grouting technique is limited by the characteristics of the backfill material and by the geometry of the bulkhead installation. Deep grouting is not possible in granular soils; it leads to side shifting of the fill, rather than deep penetration. Grout may also flow out through perforations and not help to compact soil adjacent to the perforation.

C. Rip-Rap

If the structural integrity of a bulkhead has been impaired by deterioration, a new structural support system is required, rather than encasement to prevent further deterioration. If the bulkhead is still standing and retaining the backfill, a rip-rap installation in front of the bulkhead may be an attractive solution. The rip-rap wall would be designed with sufficient bulk to resist the overturning moment of the backfill, even if the original bulkhead were entirely ineffective. The toe of the rip-rap fill would be cut into the bottom to a depth of approximately one wave-height below the normal mud line, in order to prevent undercutting caused by erosion of the support material. The rip-rap material would be graded with fine material near the wall and coarse material at the outside face, to provide a graded filter against loss of the fill material and maximum stability against wave action.

D. New Facing

One technique for preventing further deterioration of a sheet-steel bulkhead, already applied above in the concrete encasement solution, is to place a new structure between the bulkhead and the sea water. A new facing which is resistant to the marine environment can be placed in front of the original bulkhead and inert fill inserted between the two. If

the fill material keeps out further sea water contact with the bulkhead, perhaps by bonding tightly to the steel surface, the remaining structural integrity of the bulkhead should be maintained.

In concrete encasement schemes where pretreated timber is used for forming, the timber may be left in place permanently to protect the new concrete against impact and erosion. This additional protection will last until the wood formwork has deteriorated, thus adding several years of life to the concrete encasement.

As long as the original bulkhead system retains structural stability, face encasements require only enough strength to retain the fill material between the bulkhead and the new facing. Therefore, a material like corrugated cement asbestos board, which is lighter in weight and less expensive than bulk timber, could be used for this forming operation. The material used must be resistant to the erosive action of the waves and corrosive action of the sea water.

The material used to fill in the space between the new facing and the deteriorating bulkhead wall need not be concrete, but could be any inert filler capable of bonding to the face of the steel and resisting the compressive stresses imposed by static water head and wave action. It would also need to be stable in a marine environment, that is, resistant to attack from sea water and marine organisms. One of the relatively low density polymeric foams, such as polystyrene or polyurethane, might be employed for this purpose. In order to develop adequate compressive strength, foams that weigh four to five pounds per cubic foot would be required. However, the present cost of such materials is not competitive with the cost of concrete fill.

One way to cut down on the volume of fill material required would be to follow the shape of the sheet piling walls closely, rather than encasing the bulkhead with a straight, continuous form. This would result in a reduction of fill material. The economic trade-off between reduced fill cost and increased forming cost should be evaluated for any particular installation. It is doubtful that any advantage could be gained in using timber forms in a following pattern,

but the use of synthetic materials which could be formed to the proper shape during their manufacture could justify this technique economically.

E. Coatings for Repair

As the simplest form of encasement, painting or coating may be used to protect a sheet-steel piling bulkhead against further deterioration if it has not been punctured by impact or corrosion. However, it is difficult to apply coatings in the underwater and permanently wet splash zones. Since coatings cannot seal perforations against loss of fill, they must be applied before deterioration has progressed too far. It is essential to clean a deteriorated surface before applying the coating. Sandblasting, abrasion by power tools, flame cleaning, and degreasing may all be required to adequately prepare the surface.

F. Discussion of Repair Considerations

If the bulkhead structure has deteriorated to the point where it is necessary to do major repair work, an overall review of the installation is required. It may be advisable to update the structure according to more modern design standards in the course of repair. For example, a greater dredge depth or a heavier design surcharge on the backfill could be added as part of repair operations. Future maintenance and repairs might be reduced by revising the design to incorporate new, longer-life materials that were not available at the time of original construction.

Maintenance and repair operations may be hampered by the necessity of carrying them out without interfering with the operation of adjacent facilities. These requirements should be taken into consideration during the planning stage, since special techniques and delays in construction can add substantially to the cost of a repair operation.

When strengthening or otherwise repairing an existing structure to extend its useful lifetime, ingenuity should be applied to get the maximum benefit from the existing structure.

The optimal use of the existing structure is particularly important in large-scale projects where one repair technique is to be applied repetitively.

After many years of deterioration, the remaining stability of a bulkhead may be due to mechanisms other than those supplied in the original design. The existing construction should not be disturbed until it has been thoroughly checked to ascertain its long-term stability. Such a detailed check is necessary before any corrective repair can be designed.

After the deterioration of a bulkhead installation has been arrested by application of repair techniques, periodic maintenance where warranted should be instituted to prevent the occurrence of a new cycle of deterioration. If a coating were applied above the water line, for example, it should be maintained as a continuous cover.

VI. ENVIRONMENTAL FACTORS IN BULKHEAD DESIGN

In the preceding sections, numerous methods and materials for repairing, replacing, and maintaining steel bulkheads have been discussed, many of which show promise of extending the life of a bulkhead by some incremental period of time. To reduce the number of alternatives, before investigating the cost framework against which the alternatives must be judged, the environmental factors at the bulkhead site should be considered.

There are many environmental factors to be considered, and the relative importance of each varies with the bulkhead site. In some locations, economic factors such as availability of funds, proximity of dependent structures, and availability of skilled personnel may predominate in the selection of a material system. In other locations, climatic conditions and biological factors are most important in the selection of a bulkhead system. No two locations are subject to the same conditions, and significant variations can even be found within the same harbor. While it is not possible to review all environmental factors in this study, the more important ones are discussed, and the conditions under which these factors are important are reviewed.

A. Economic Environment

The economic environment is made up of several factors. For example, availability of funds will determine whether or not work can be done. The cost of failure must be considered, including the cost of potential damage to adjacent facilities. Finally, administrative personnel, contractors, inspectors, and other skilled people must be available.

Funding

Obtaining funds for public works is always difficult and bulkhead work usually does not have a high proirity, since a bulkhead mainly has a passive role in the mission of a base. Bulkhead projects compete with many other projects for available maintenance and repair funds. At present, expenditures for installation of a bulkhead are usually tied to a larger project. Although replacement of old installations might be desirable, their repair may be the only course of action possible due to financial constraints.

Cost of Failure

Another important consideration in bulkhead facility studies is the cost of failure if the bulkhead fails to perform the specified function. This cost must include shore front repairs preparatory to replacing the bulkhead and any repairs to adjacent facilities such as utility lines, roadways and structures. The changes on the sea side must also be considered because the sudden failure of a bulkhead near a channel may affect shipping in the area.

When the cost of failure is high, the design safety margin must be set higher, and the bulkhead must be inspected frequently to watch for signs of failure. In these bulkhead replacement studies, no residual value is placed on the existing structure. In fact, additional costs may be incurred in order to remove or remodel the existing bulkhead.

Availability of Maintenance and Repair Facilities and of Personnel

Contracting for work on any scale involves administrative costs for drawings, specifications, inspection, and other services. The cost of administering a small repair or maintenance project may become a large portion of the total cost of the work. The availability of Naval public works personnel familiar with bulkhead inspection, maintenance, and repair can be a determining factor in the selection of methods used to maintain a bulkhead structure. With competent personnel on site, good local contractors and utilities available, a decision can be made to preserve a bulkhead beyond marginal end-of-life conditions with the certainty that any problems which arise can be handled.

B. Sea, Shoreline, and Weather

Climate, tide, and wind velocity and direction must be considered in the bulkhead design. Temperature variations determine the frequency of freezing and thawing cycles which can be deleterious to concrete. The corrosion rate is strongly influenced by water temperature. Also, high water temperatures promote the presence of marine borers.

Wind direction and force and the shoreline contour dictate the surf and spray conditions to which the wall is subjected. Heavy surf not only creates a wider splash zone with concentrations of salt water on and behind the wall, but the pounding may loosen bolts attaching the bulkhead to wales and tie-rods. Greater mass, as represented by concrete and rip-rap, is effective in blunting the effects of heavy surf.

Rain and snow can accentuate freezing and thawing cycles by keeping the surface of the bulkhead wet at all times. They also affect the ground water level which in turn affects the lateral loading on the bulkhead and the stability of the anchoring system. Finally, rain and snow may collect behind the bulkhead and accentuate corrosion on the inside of a steel bulkhead or wash fill through holes in the structure.

Tidal variations and water depth determine the extent of normal wetting and drying and thus largely dictate the extent of exposure to corrosion.

Water depth also is a factor in determining where electrochemical reaction will be most pronounced and whether conditions are conducive to scouring by ocean-borne particles. The mud line location and the contour of the ocean bottom, as well as tidal currents and wind direction, dictate wave conditions and thereby affect the size of the splash zone, the impact loading on the bulkhead, and the scour patterns. Proximity to channels or marine structures may prevent certain types of repairs (i.e., rip-rap). Experience with bulkhead structures under similar meteorological conditions should be reviewed before a design is finalized.

C. Biological Environment

In certain environments, marine life and biological organisms can affect the bulkhead. This situation can occur when the temperature and condition of the sea water is favorable to the rapid development of marine borers or vegetation, and the bulkhead material is prone to attack by marine life. Likewise, heavy pollution of the water may promote the decomposition of bulkhead materials. Fortunately, polluted water

inhibits the development of marine life so that these effects tend to offset each other.

Marine borers, barnacles, and vegetation attached to bulkhead walls can accelerate normal corrosion and erosion patterns. Lacking experience with timber structures at an intended location, it is wise to place some wood samples in the water to test for marine attack before selecting a structural design with exposed timber. Preservatives will seal timber from attack by marine life, but the preservation must be done under factory conditions; the same degree of protection cannot be obtained on the construction site. Wherever possible, timber structures for marine use should be prefabricated and treated at the mill. If the preservative coating cannot be kept completely intact during installation, it may be impractical to use a timber facing, or it may be necessary to sheath exposed wood with aluminum or copper.

Pollution in sea or harbor waters usually does not affect structures as much as electrochemical corrosion or rusting. When pollution is severe, however, it may cause extensive corrosion. The section of a wall nearest to the sewage-laden effluent is the area affected most severely. Peak corrosion may take place at or near the mud line when sludge is allowed to accumulate. If pollution is the major problem, concrete is the most desirable structural material because steel and timber are both affected by chemical and biological pollutants.

D. Other Factors

Other factors that may have a bearing on bulkhead material selection are:

- the presence of stray currents;
- the development of a thick scale on steel or heavy vegetation on timber; and
- mechanical abrasion and impact loading due to ships.

When any of these factors outweigh normal wear due to erosion and corrosion, the bulkhead design must be tailored to fit these special conditions.

Stray currents due to electrical generators, radio and microwave equipment, and faulty transformer grounds accelerate the decomposition of sheet-metal piling, fasteners, and concrete reinforcing bars. Direct current sources are especially dangerous. The source of the current does not have to be close to the bulkhead to affect it. In many cases, electrical equipment is grounded to a soil pipe which, if placed in wet soil, can carry a stray current a long distance. If tests or previous experience have shown the presence of ground currents, cathodic protection of steel or use of electrically inert materials may be necessary.

The nature and thickness of scale and attached marine life may prevent the use of some maintenance and repair techniques, since most coating materials and penetrants must be applied over a clean dry surface. If scale cannot be removed or must be removed with great difficulty, maintenance may become impractical. Sandblasting or peening of a heavily corroded wall may result in perforation. In cases of this type, replacement may be the only solution. Also, the removal of vegetation from timber may expose the structure to borers.

Each of the environmental factors considered may be predominant enough to affect the design of a bulkhead or to alter the use of bulkhead installation, maintenance and repair methods, or materials. Usually, however, a combination of environmental factors is required before a change in the design or the selection of methods and materials is necessary. In order to arrive at the best design, the effect of the environment on bulkheads in the area should be studied and a combined value placed on all the environmental factors for economic and design evaluations.

VII. ANALYSIS OF BULKHEAD INSTALLATION, MAINTENANCE, AND REPAIR COSTS

The methods and materials adaptable to shoreline construction have been explored in Sections III, IV, and V, and the environmental factors relating to design and installation have been examined in Section VI. In this section the economics of bulkhead construction and maintenance will be explored.

A. General Cost Considerations

In the fiscal sense, a bulkhead represents a stream of payments in return for a service performed to the Navy. A certain sum is expended for initial installation of the bulkhead. Additional sums may be spent at some future date to maintain or repair the wall. Finally, when the original structure is no longer able to perform its function, additional money is spent to replace it. If the functional requirement for a wall continues, the stream of payments goes on indefinitely.

Comparison of two or more alternative bulkhead systems is complicated by the fact that expenditures may not take place in the same years. The problem of comparing non-uniform expenditures over varying periods of time, where money has a time value, can be simplified by using the annual cost method. The annual cost method allows the analyst to reduce the actual expenditures during the life of the bulkhead to a series of uniform yearly payments. In essence, the annual cost represents the amount that would be paid each year to amortize the initial installation costs, the interest accumulated on that sum, and all maintenance and repair costs until replacement. Then, the replacement cost may also be amortized at the same rate. Classically, a comparison drawn on this basis should cover the alternatives over an equal period of time. However, when the comparable time periods represent one or more bulkhead replacement periods, differences due to amortization periods are insignificant.

There are three major factors involved in developing an annual cost profile for bulkheads. The initial installation cost is the initial outlay for the wall, and it should include the material costs, transportation costs, and on-site handling and driving costs. For a bulkhead, it is customary to include the cost of anchors, tie-rods, and wales, as well as excavation and backfilling costs.

The lifetime of the bulkhead is the major factor which is most difficult to ascertain with any degree of reliability. A bulkhead is considered to be performing its specified function when it maintains a semi-impervious barrier between the sea and the shoreline. The end of lifetime can be defined by any one of the following three conditions:

- collapse or buckling of a significant portion of the bulkhead;
- gross loss of backfill through holes in the bulkhead; or
- frequent and expensive maintenance to keep the bulkhead in service.

The latter conditions are hard to measure and it is possible for a bulkhead to be close to failure for a period of years. Thus, a measure of bulkhead lifetime is difficult, but it must be made for economic evaluations.

Several approaches are available to the estimator. A design life is usually specified by the designer and it is his estimate of how long the bulkhead will meet its function under normal conditions in that area. The design life will be determined from the stresses to which the wall is subjected, the section required to resist the applied stresses, the margin of safety allowed in the design, and the corrosion rate in the area. Usually failure results from excessive loss of fill through holes in the bulkhead. Since the maximum web for sheet-steel piling is 3/8 inches (.375 inches) and the design manuals show a maximum loss of 10 to 20 mils of steel per year because of corrosion, the web will show perforations in 20 to 35 years. Thus, a design life of 20 to

years for an unprotected sheet-steel bulkhead is reasonable. An estimate of historical lifetime can often be made from records kept about pile installations in the area. For example, experience has shown that a sheet-steel pile installation will last 30 to 40 years in New York harbor.

Perhaps the most important estimate that can be made is the mission lifetime of the bulkhead. The purpose that the wall was intended to serve may change or in fact disappear over a period of years. Depending on the type of installation, it may be possible to prescribe a specific need for a long period of time or predict with some assurance that the function will change. For instance, a cargo wharf is built for a specific purpose and unless the port ceases to be used or ships become much larger or require more draft, the wall may be in service for many decades. On the other hand, almost all airfield structure may have to be redesigned as larger aircraft with greater speeds come into service. Part of any engineering economic analysis should be a study of the mission requirement for a structure and comparison of this factor with the design lifetime.

The lowest value of design lifetime, historical lifetime, or mission lifetime should be used in economic evaluations.

The <u>time value of money</u> is the third factor in determining the cost profile. Over a long replacement cycle, the time value of money may vary significantly. In a study such as this one, which deals with government funds, however, it is reasonable to use an interest rate approximating the rate for government bonds, which in turn represent the U.S. Government borrowing rate.

B. Baseline Configuration

When the annual cost variables can be projected with some accuracy, all alternatives for bulkhead construction and repair can be costed and compared with each other. When one or more variables cannot be projected with accuracy, comparisons can best be drawn against a baseline configuration which represents a normal bulkhead situation with known

costs and lifetime. In this report, the baseline condition is a sheet-steel bulkhead installed with no protective coatings or cathodic protection and no maintenance prior to the time of repair or replacement.

The annual cost of a sheet-steel bulkhead can be calculated using the formula:

$$\text{Annual cost} = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

where:

- P = initial installation cost in dollars per linear foot
- n = lifetime in years
- i = time value of money in percent

This formula assumes that there will be no salvage value at the end of functional lifetime (assumed throughout the study). Using an interest rate of 5 percent, and allowing the initial installation cost to vary from $140 to $500 per linear foot and the lifetime to vary from 20 to 50 years, a series of curves is generated which cover the annual costs of a wide range of installations (see Figure 17). It should be noted that it is possible to generate a similar series of curves, using other interest rates.

The family of curves can be used to provide an annual cost under any given set of conditions. For instance, the fiscal year 1967 program cost estimate for NAS(NY) estimates the cost of replacing sheet-steel piling, using existing tie-rods and anchors, at $288 per linear foot. The cost of installing a new wall with tie-rods and anchors is estimated at $380 per linear foot. The annual cost per linear foot for these installation over a 25-year life would be $20.40 and $26.90, respectively.

C. Evaluation of Systems with Additional Installation Costs In Extending Bulkhead Life

A bulkhead system which will cost more than a conventional carbon steel bulkhead can be justified economically

Figure 17

ANNUAL COST OF BULKHEAD AS A FUNCTION
OF INSTALLATION COST AND LIFETIME

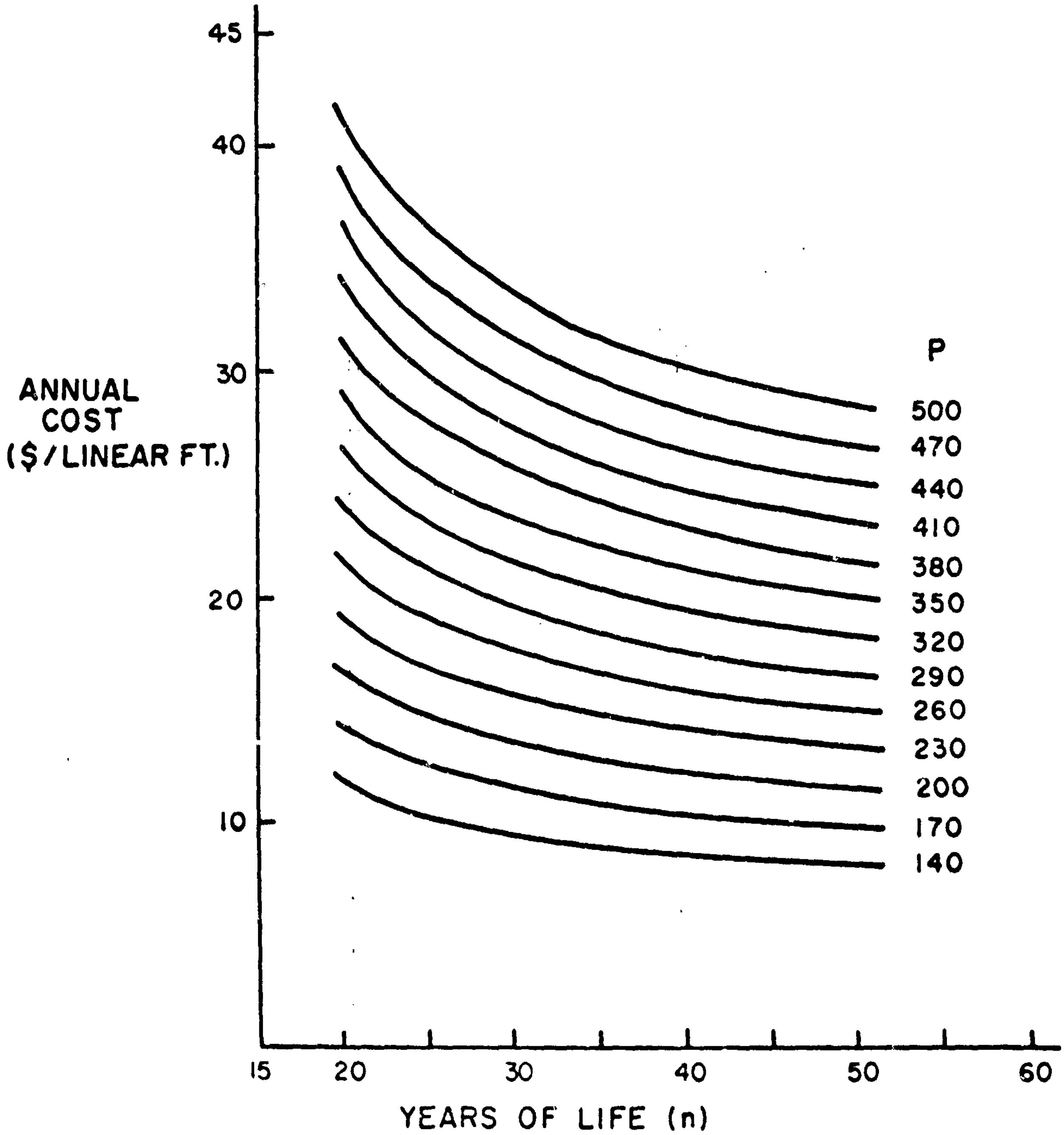
$$\text{Annual Cost} = P\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$$

where:

P = initial installation cost \$/linear foot

i = interest rate (5%)

n = years of life



if the functional lifetime of the wall is extended by the use of additional funds. Several systems discussed in Section II fall into this category, including special steels, piling constructed from metals other than steel, and concrete bulkheads. The same analytical approach applies to protection systems which can be added to a carbon-steel bulkhead at installation, such as cathodic protection (sacrificial anodes only) and initial coatings. The additional cost of protection systems must result in added lifetime.

The formula for determining how much additional investment over and above the initial installation cost of carbon steel piling can be justified by extending the life of the wall is as follows:

$$(P+X)\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

where:

P = initial installation cost in dollars per linear foot
n = lifetime in years
i = time value of money in percent
X = additional investment in dollars per linear foot
y = extension of lifetime in years

The solution for either of the new variables can be obtained by using the same family of curves generated in the baseline configuration (see Figure 18). An additional expenditure of X dollars per linear foot moves the initial installation cost up to a new curve represented by P+X. The distance along the horizontal line connecting the original lifetime on curve P with the new curve P+X represents the additional lifetime which has to result to equate the two systems in annual cost. For example, assume a replacement carbon steel piling wall with coating will cost $290 per linear foot and last for 25 years. If a special steel piling wall with coating and cathodic protection costs $335 per linear foot, how much additional lifetime will it have to yield to be cost effective in comparison with carbon steel piling? First, draw a curve representing P+X or

Figure 18

NOMOGRAPHS FOR DETERMINING INCREMENTAL INVESTMENT WHICH CAN BE JUSTIFIED BY LIFE EXTENSION

$$(P + X)\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

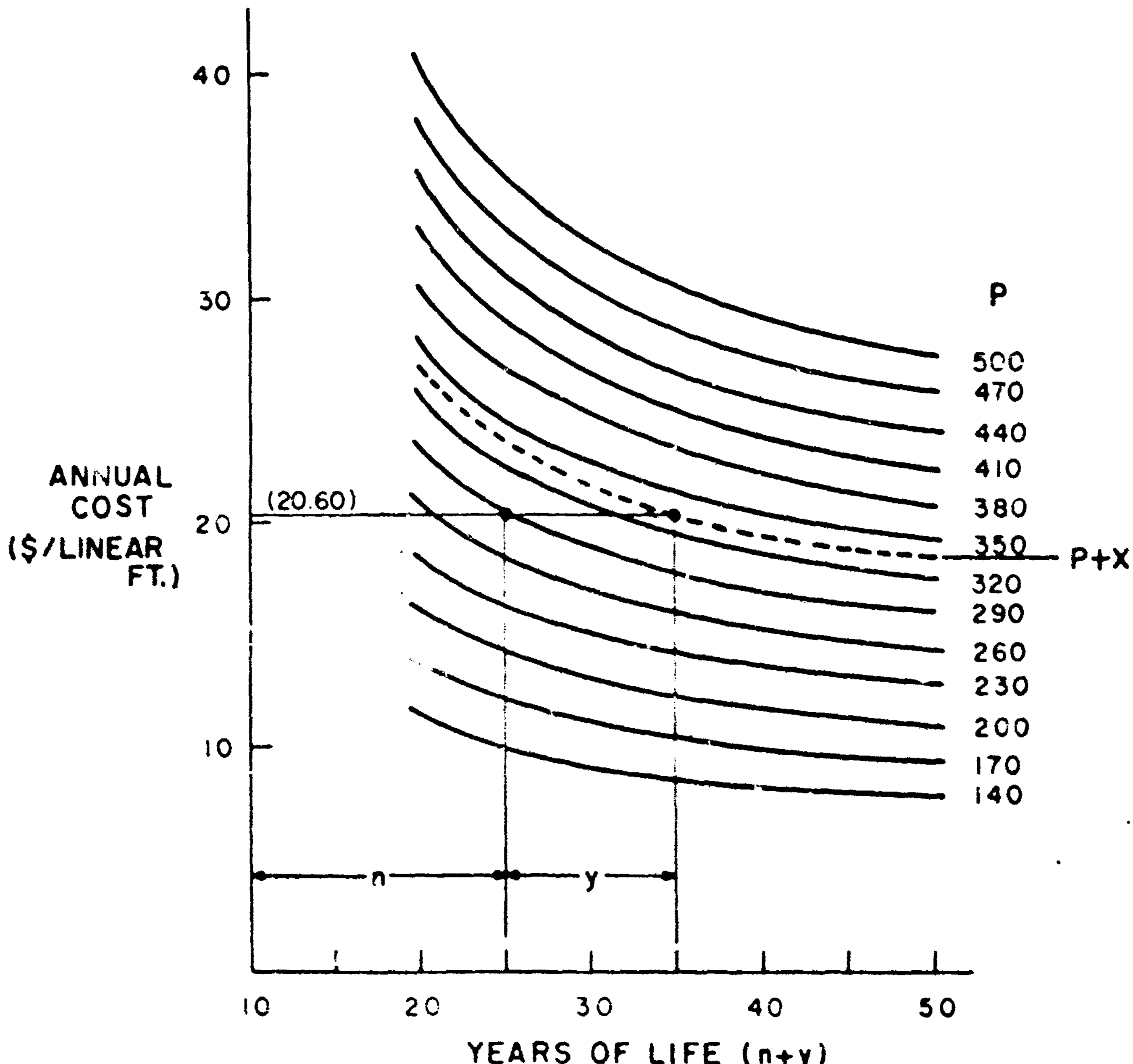
where:

P = initial installation cost $/linear foot

i = interest rate (5%)

n = lifetime in years

X = maximum expenditure per linear foot for additional installation methods that will extend the lifetime by y number of years



$335 per linear foot. Then, connect the point representing 25-year lifetime on the P curve ($290 per linear foot) and the new curve with a horizontal line. The answer is 10 years of additional life, which will justify the increased expenditure.

Some general conclusions can be drawn by observing the juxtaposition of the curves in Figure 18. First, if the baseline configuration lasts 20 years or less, increased expenditures of 20 percent or more can be justified by less than 10 years of additional life. As the baseline configuration increases in functional life, the increased installation expenditures must be justified by much longer extensions of bulkhead life. Second, if the baseline configuration lasts even 20 years, as the bulkhead at the NAS(NY) has done, no amount of additional life will justify an expenditure of more than twice the initial installation cost. This observation effectively rules out the use of high-cost metals, such as titanium or nickel, or concrete cast-in-place to considerable depths. Third, a relatively small incremental installation cost such as coating (5 to 15 dollars per linear foot), installation of cathodic protection (10 to 15 dollars per linear foot), and concrete coping (20 dollars per linear foot) can be justified with a very short increase in the functional lifetime when the original bulkhead lifetime without these features is 25 years or less.

D. Evaluation of Annual Maintenance Costs in Extending Bulkhead Life

Annual maintenance may be economically undertaken if the cost is less than the reduction in annual cost engendered by increased lifetime. Among the techniques which could be performed on an annual basis that may extend lifetime are painting, scaling and defouling, and impressed current cathodic protection.

The formula for determining how much annual maintenance can be performed to develop a life extension of y years is as follows:

$$(A+P)\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

where:

A = annual maintenance costs in dollars per year.

The solution for either the annual maintenance cost or life extension variable can once again be obtained by using the same family of curves (see Figure 19). A horizontal line is drawn to the ordinate from the point representing initial installation cost and estimated lifetime. Another horizontal line is drawn from the point on the initial installation cost curve and the extended lifetime. The distance between the two lines, when evaluated against the annual cost scale, represents the annual maintenance cost which can be expended to extend life by that period of time. For example, if initial installation costs are $350 per linear foot and estimated life without maintenance is 35 years, one can spend less that one dollar per linear foot per year to extend life by five years.

This example demonstrates the apparent futility in scheduling annual maintenance. Unless the unmaintained life is very short, the amount which can be spent annually for maintenance precludes any thorough work or any expensive coating materials. Some of the lowest cost coating materials cost the user 60 to 85 cents per square foot to apply. If the tidal and splash zones cover 8 to 10 feet and using a multiplier of 1.3 feet of piling surface per foot of wall, a coating application would cost at least $6 to $10 per linear foot of bulkhead. Annual maintenance in almost any form for sheet pile bulkhead walls appears to be too expensive to be justified in lengthened lifetime.

E. Evaluation of Periodic Maintenance Costs in Extending Bulkhead Life

Although annual maintenance does not appear economically justifiable, periodic maintenance might be economically

Figure 19

NOMOGRAPHS FOR DETERMINING THE MAXIMUM ANNUAL MAINTENANCE COSTS WHICH CAN BE JUSTIFIED BY LIFE EXTENSION

$$A + P\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

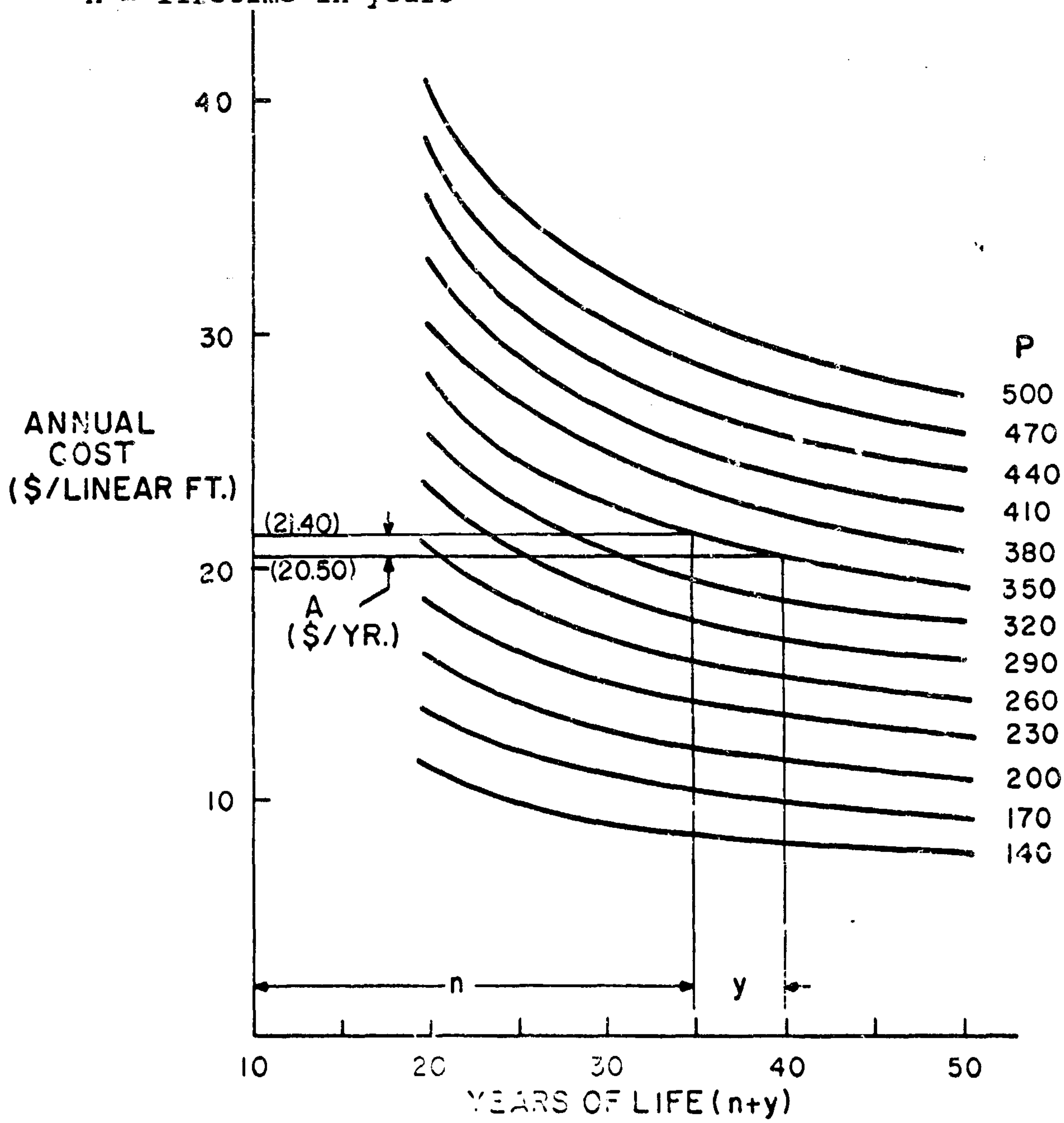
where:

A = maximum costs ($/year) for annual maintenance projects that will extend bulkhead lifetime by y number of years

P = initial installation cost $/linear foot

i = interest rate (5%)

n = lifetime in years



sound, especially if the methods used provide good protection between maintenance cycles. Adherent coatings, cathodic protection installations of both sacrificial anode and impressed current types, and grouting are methods that may be performed in 5- to 10-year cycles that provide sound protection over the cycle period and provide promise for extension of the functional lifetime.

The formula for determining how much maintenance work can economically be performed each period, involves a combination of present value and annual cost concepts. It is as follows:

$$P\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] + \left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right]\left[\sum_{k=1}^{k=T} M\left(\frac{1}{(1+i)^{ka}}\right)\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

where:

M = amount of maintenance work in dollars per linear foot
a = maintenance cycle in years

and

$T = \frac{n+y}{a} - 1$, rounded up to the next higher integer for fractional values.

M is the maximum amount of maintenace cost each a years to extend the life of the wall by y years beyond the normal life span. Figures 20 and 21 show the graphical solution curves for maintenance on 5- and 10-year cycles for various normal life spans and life extensions. With the many variables present, it was difficult to graphically present values of M for many initial installation costs. The initial installation cost was set a $290 per linear foot in Figure 20. Solutions for other installation costs can be ratioed from the graphical solutions.

Figure 20

NOMOGRAPHS FOR DETERMINING THE MAXIMUM PERIODIC MAINTENANCE COSTS WHICH CAN BE JUSTIFIED BY LIFE EXTENSION

$$P\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right]+\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right]\left[\sum_{k=1}^{k=T} M\left(\frac{1}{(1+i)^{ka}}\right)\right]\leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

where:

$T = \left(\frac{n+y}{a} - 1\right)$ rounded to next higher integer for fractional values

P = initial installation cost \$/linear foot

i = interest rate (5%)

n = years of life

M = maximum maintenance cost each $\underline{a}$ years, which will extend the life of the wall by y number of years

MAINTENANCE EACH FIVE YEARS

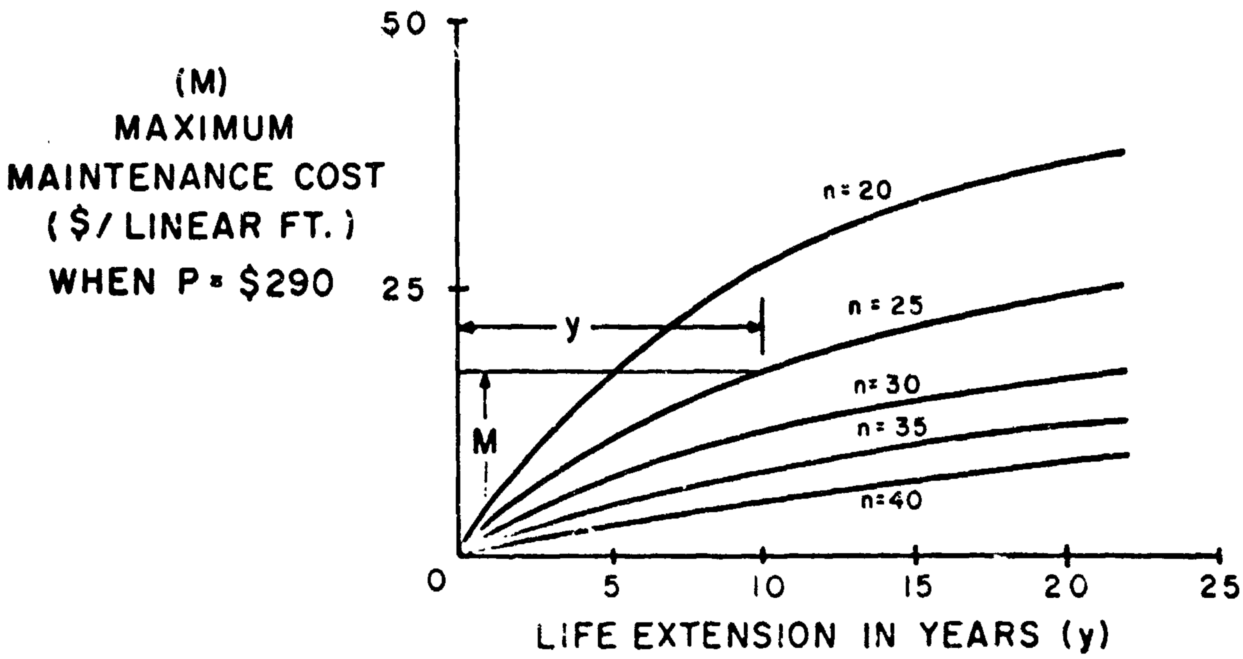


Figure 21

NOMOGRAPHS FOR DETERMINING THE MAXIMUM PERIODIC MAINTENANCE COSTS WHICH CAN BE JUSTIFIED BY LIFE EXTENSION

$$P\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] + \left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right]\left[\sum_{k=1}^{k=T} M\left(\frac{1}{(1+i)^{ka}}\right)\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

where:

$T = \left(\frac{n+y}{a} - 1\right)$ rounded up to next higher integer for fractional values

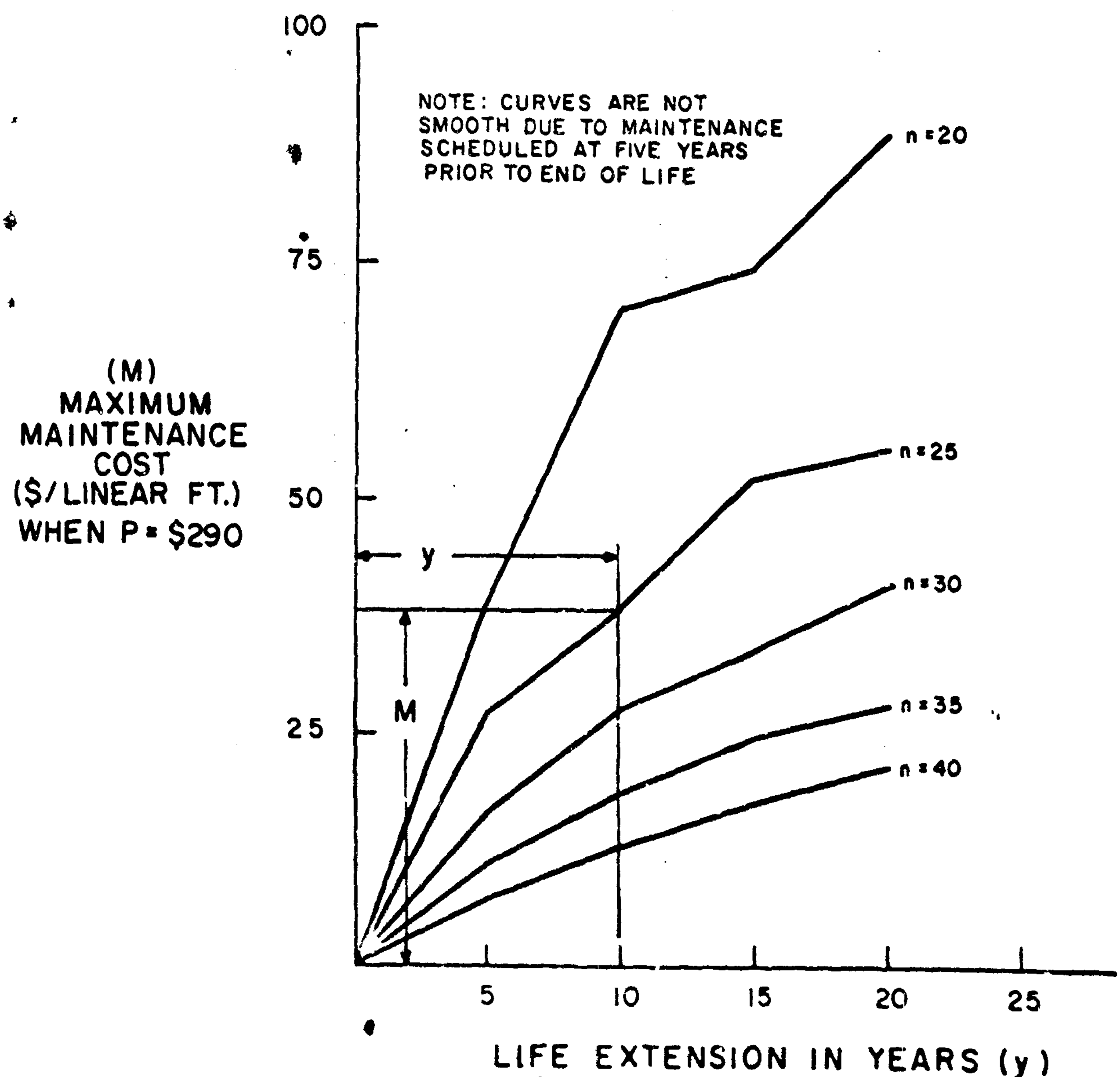
P = initial installation cost \$/linear foot

i = interest rate (5%)

n = years of life

M = maximum maintenance cost each $\underline{a}$ years which will extend the life of the wall by y years

MAINTENANCE EACH TEN YEARS



A solution to a given set of circumstances may illustrate the feasibility of periodic maintenance. A wall that had an initial installation cost of $290 per linear foot is expected to have a life of 25 years. How much maintenance can be done each five or ten years to extend life by ten years? The solutions are $16.90 per foot each five years or $38.30 per foot each ten years. The former figure would allow thorough cleaning and coating down to the tidal zone. The latter figure may even allow for underwater cleaning and application of coating. There appears to be sound justification for periodic maintenance if adequate life extension can be demonstrated, especially in cases where design life is 25 years or less.

F. Evaluation of Repair Systems in Extending Bulkhead Life

As discussed previously in Section III, a sheet pile bulkhead wall deteriorates unevenly. The area from slightly below the tidal zone to the splash zone may be approaching failure, while the top and bottom of the bulkhead are still serviceable. The steel piling driven below the mud line, which is not corroded, can be a very strong foundation for additional construction. There are repair methods that can be used near the end of the normal life span of the bulkhead which use the non-corroded steel as a basic part of a life extension system. Three of these methods were used at the NAS(NY) and will be thoroughly examined in Section IX.

Two approaches must be taken to the determination of how much can be spent on a repair system to justify additional life. When the bulkhead is approaching the end of lifetime, a simple comparison can be drawn between the annual cost of the replacement system and the annual cost of the repair system. The curves shown in Figure 22 can be used to perform the comparison.

When a comparison must be made earlier than the end of lifetime between replacement or repair at some future date, the formula for determining how much can be spent at the end of normal life to extend the lifetime by some period of years is as follows:

Figure 22

NOMOGRAPHS FOR DETERMINING THE MAXIMUM REPAIR COSTS WHICH CAN BE JUSTIFIED BY LIFE EXTENSION

$$P\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] + L\left[\frac{1}{(1+i)^{n}}\right]\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] \leq P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

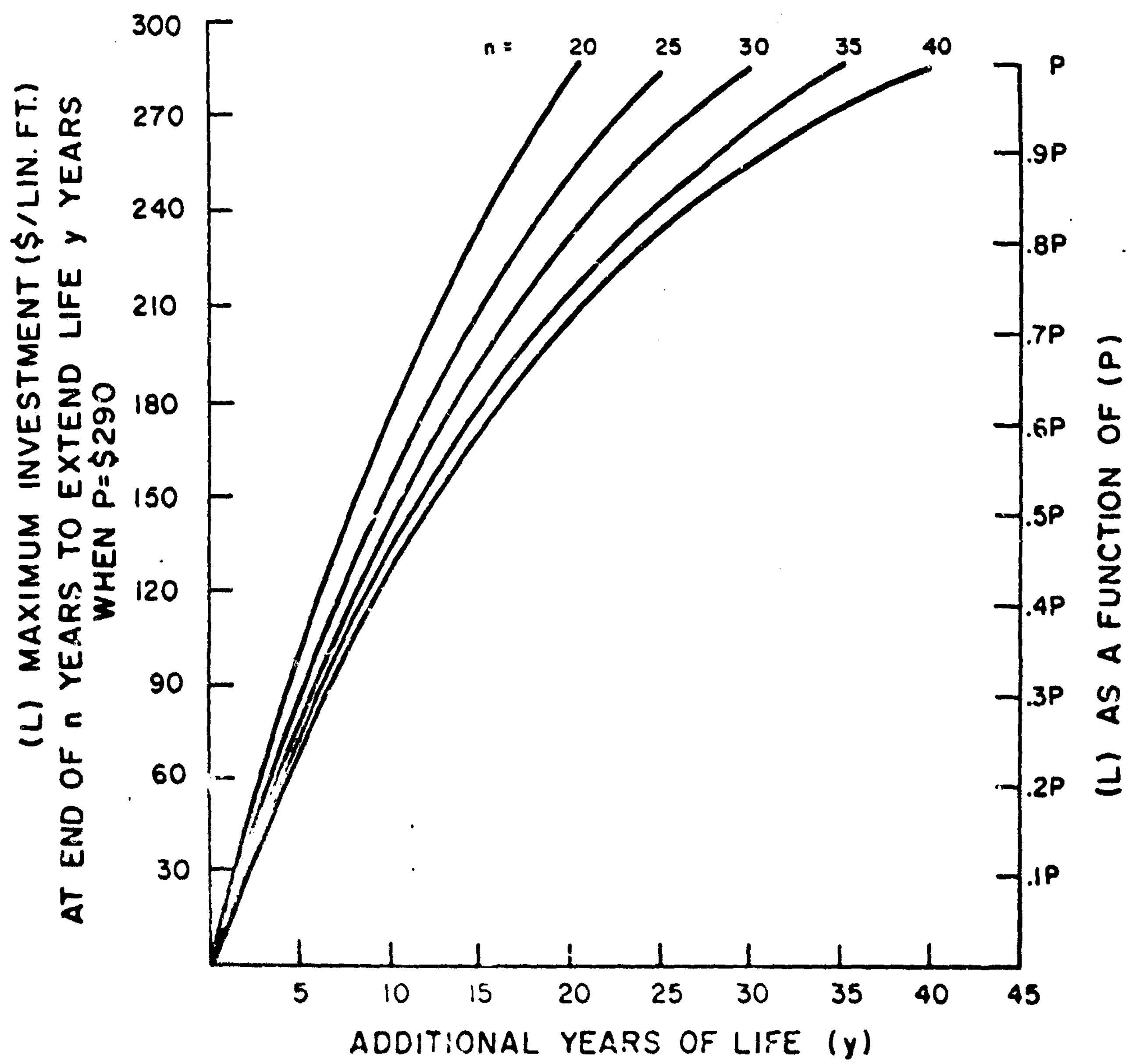
where:

P = initial installation cost \$/linear foot

i = interest rate (5%)

n = years of life

L = maximum investment (\$/linear feet) in renovation of wall at the end of n years which will extend the life of the wall by y years



$$P\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] + L\left[\frac{1}{(1+i)^{n}}\right]\left[\frac{i(1+i)^{n+y}}{(1+i)^{n+y}-1}\right] \leq$$

$$P\left[\frac{i(1+i)^{n}}{(1+i)^{n}-1}\right]$$

where:

L = renovation investment in dollars per linear foot

and

n, y, and P are as defined previously.

A set of solutions for the maximum dollar renovation investment is shown in Figure 22. The results shown in this figure are based on an initial investment of P, and all values of L can be ratioed from the curves.

The interesting conclusions to be drawn from analysis of this data are as follows:

- Over 50-percent of the original cost can be spent for ten more years of life if the original life is less than 30 years.
- The possibility appears to exist for series of repairs each 1ᴗ to 15 years if the structural integrity of the sheet-steel foundation and tie-rods remains intact.
- One can invest a fairly significant sum (over one-third of the replacement cost) to obtain just five years additional life.

With such interesting possibilities for repair methods, there appears to be room for some imaginative engineering at the end of the normal lifespan of a steel bulkhead.

G. Cost Considerations in the Selection of Replacement, Maintenance, and Repair Methods

Consideration has been given to additional investments at the installation of a bulkhead, during its normal lifespan, and at the end of normal lifespan, and there appear to be cost effective investment opportunities at all stages. These are based on life extension beyond normal expectancy and therefore presuppose a functional requirement for the wall to the end of the additional life expectancy or beyond. It should be noted in closing that the restriction to an interest factor of 5 percent was made for expediency; the interest factor can be varied. Raising the interest factor will make additional investments to achieve longer life even more attractive, while lower interest rates will require longer payout periods. Also, all comparisons have been drawn against the baseline configuration. If modifications have been made to achieve lower annual costs, then the new figures become the baseline against which all similar systems must be measured.

VIII. BULKHEAD SYSTEMS WITH POTENTIAL ECONOMIC APPLICATION BY NFEC

Of the materials and methods analyzed for application in bulkhead construction, maintenance, and repair, some did not appear to offer the potential for additional life in service, some did not appear to fit the environmental requirements in shoreline construction, and some were too costly to be advantageous. There appear to be eight material and method systems that fit the environmental and economic conditions in the Eastern Division. These systems are all applicable to shoreline protection of the bulkhead or sea wall type and can be amplified to provide foundation protection in cases where cost of failure is high. They are applicable in conditions where moderate depths of water are on the sea side of the wall and some earth is retained over the mean high water level on the shore side. These bulkhead or sea wall systems are not designed for heavy vertical loading or lateral loads well in excess of normal earth pressures, but in most cases, these systems can be adapted to perform more than their basic function of shoreline protection.

No one system is generally superior under all design conditions. Some are better in shallow-water conditions, some in deep-water conditions, and some in heavily used channels. Others cannot be used in areas where ships will be docking. For these reasons, and to illustrate comparative economic advantages, three shoreline profiles that are typical of conditions met in actual experience were selected for comparison of alternatives (see Figure 23). In the first profile, the ocean floor level is in the tidal zone; in the second profile, the ocean floor level is slightly below mean low water; and in the third profile, the ocean floor level is far enough below mean low water to allow ships to dock against the bulkhead. In all cases, a ground level of 10 to 12 feet above mean low water has been assumed.

The systems selected for detailed analysis in the three shoreline designs can be further classified into replacement, repair, or maintenance techniques. Replacement systems either replace the old sheet piling wall or functionally suppress in favor of a new system. The replacement systems selected for detailed analysis include:

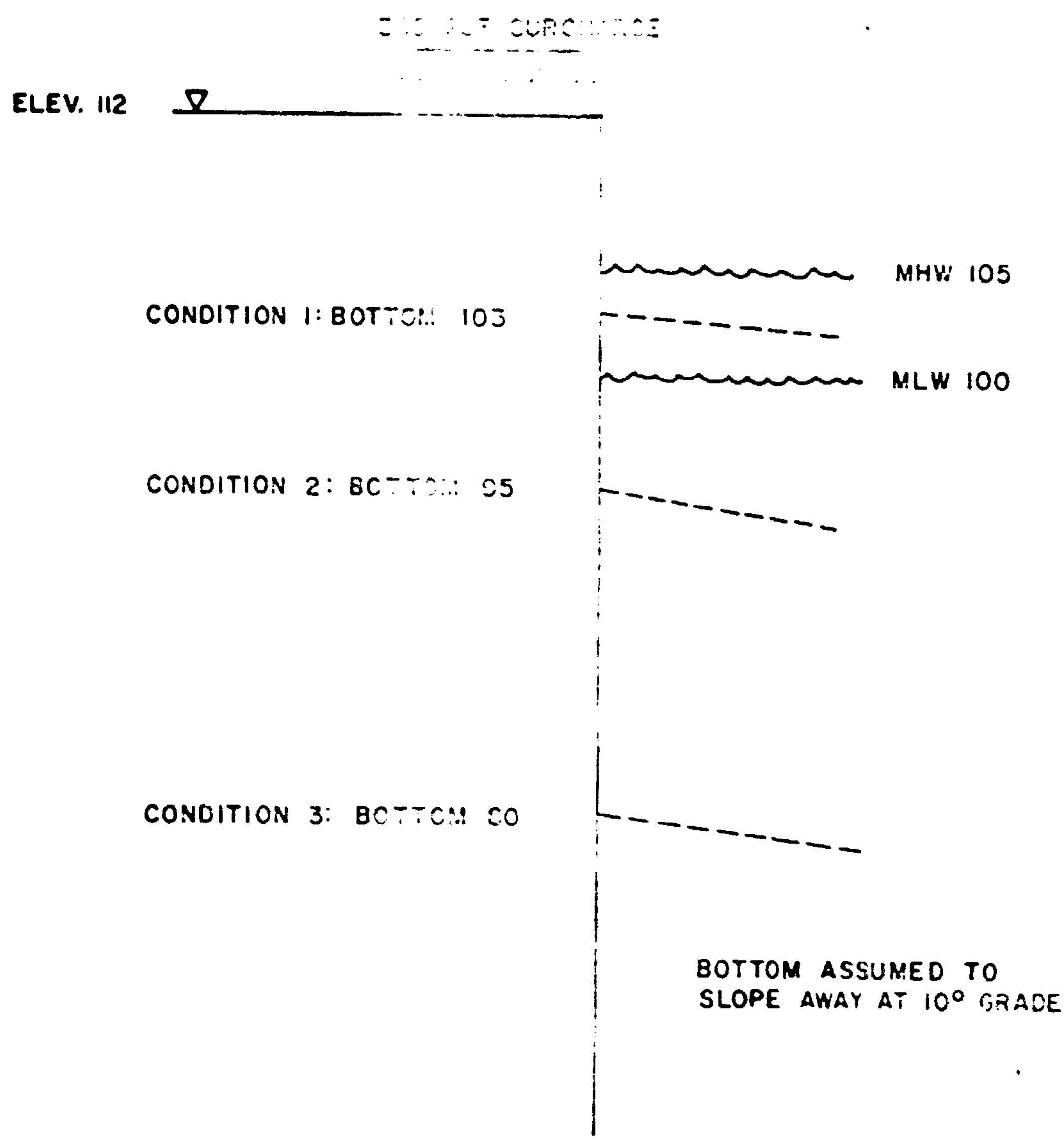


FIGURE 23 – [illegible] PROFILES

- special steel piling for marine applications;
- carbon steel piling with initial protection; and
- rip-rap sea walls.

The repair systems selected are:

- concrete reinforcing on the shore side;
- replacement of the bulkhead in the tidal zone with concrete; and
- composite wall with timber, concrete, and steel.

These repair systems are similar to types A, B, and C construction at the Naval Air Station, New York.

The maintenance systems selected are:

- application of coatings; and
- mortar grouting.

Direct cost comparisons can be drawn between repair systems and between repair and replacement systems. Presumably, the designer has a choice of repairing or replacing when a bulkhead nears the end of functional lifetime. The cost of a maintenance technique must be compared against the cost of another maintenance system or the alternative of no maintenance because it does not appear to be economical to replace or repair a bulkhead during its functional lifetime.

A. <u>Replacement System - Special Steel Piling for Marine Application</u>

The development of a special high-strength steel for marine applications has provided the designer with a reasonable alternative to replacement with another carbon steel bulkhead. As discussed in Section III, this special steel forms a tightly adherent corrosion product that resists further rusting and scaling. This steel can be depended on to provide longer serviceable life in the splash zone region.

Furthermore, the higher strength of this steel means that a lighter section can be used for the same design condition, thus offsetting the additional cost of the special steel piling. A design change involving the use of lighter piling usually results in the specification of a steel piling with a thinner flange and the same web section. Thus, the web, which is perforated first in cases of advanced corrosion, is not affected by such design changes. Special steels cost from 20 to 25 percent more than standard carbon steel but when transportation, driving and installation costs are included, the cost disadvantage narrows to less than 10 percent. If the additional strength of the special steel permits a change in design to a thinner piling section, the special steel piling installation can actually be made at a lower total cost. If, however, the same piling design is used, the special steel has to provide some additional lii to be economically justifiable.

A cost comparison between special steel for marine applications and carbon steel piling in the 3 design conditions of Figure 23 is shown in Figure 24. It is evident that the special steel provides significant cost advantages if it can remain in service five or more years after a carbon steel bulkhead must be replaced. The effect of adding cathodic protection and coating systems to both the special steel and carbon steel bulkheads on initial installation would be to prolong the useful life of both and thereby require an even greater advantage in the extension of useful life for the special steel.

Special steels have the advantages of slow and even corrosion product development and greater strength. In

Figure 24

COMPARISON OF ANNUAL COST OF SPECIAL STEEL BULKHEADS AND CARBON STEEL BULKHEADS

	Section Modulus of Piling Per Ft. of Wall ($in.^3$)	Weight Per Sq. Ft. of Wall (lbs.)	Length of Piles (ft.)	Cost Per Linear Ft. ($)	Estimated Life (yrs.)	Annual Cost ($)
Condition 1						
Special Steel	5.4	22.0	29	190	35+	11.60
Carbon Steel	5.4	22.0	29	180	20-30	14.40-11.60
Condition 2						
Special Steel	5.4	22.0	37	252	35+	15.40
Carbon Steel	5.4	22.0	37	240	20-30	19.20-15.60
	10.7	27.0	37	253	20-30	20.30-16.40
Condition 3						
Special Steel	30.2	27.0	52	375	35+	22.90
Carbon Steel	30.2	27.0	52	354	20-30	28.30-23.00
	38.3	32.0	52	373	20-30	29.90-24.30

areas where particle abrasion is high or where vessels or flotsam are scraping against the exposed surface of the bulkhead, the corrosion product formed on the special steels covers the exposed steel area with a dense impermeable oxide in contrast to carbon steel, which when scraped may develop a weak area which can corrode at an increasing rate. The added strength means that for a similar design the safety margin in special steel is far greater and that the same cross-section of uncorroded metal can be relied on to support additional stress loading. Balanced against these considerations is the additional cost of the special steel which may require a longer payout period.

When the cost of failure of a bulkhead is high, when the accessibility to a bulkhead is limited, or when maintenance and repair costs are high, the advantages gained by using special steels are emphasized. When the mission life is certain to be long, special steels are also desirable. When mission lifetime is uncertain, when maintenance is easily accessible and low in cost, and when the cost of failure is low, special steels may not compare favorably with standard carbon steel.

B. Replacement System - Carbon Steel Piling with Initial Protection

The rate of corrosion of carbon steel piling varies significantly from the mud line to the top of the piling. Peat corrosion rates occur in the splash zone and the zone just below mean low water. In addition, piling exposed to the atmosphere at the top can corrode at a rapid rate. Systems which will retard corrosion over the entire piling surface, or retard corrosion in peak corrosion zones and thus produce an even corrosion rate, can provide the conditions for longer bulkhead life.

The three initial protection methods which show the most promise in corrosion retardation are as follows:

- coating the exposed surface above the mud line;
- installation of cathodic protection; and
- capping the bulkhead with concrete coping.

Coatings

An application of coal-tar epoxy or equivalent coating material will last from 2 to 5 years according to tests performed at the Naval Civil Engineering Laboratory and other locations. If corrosion proceeds from the end of initial protection at a rate similar to an unprotected surface, the extension of lifetime will be the same 2 to 5 years. This is by no means certain, but it does seem logical that the 2 to 5 years of protection will result in some life extension.

The cost of an application of coating material prior to pile driving will vary between $.35 and $.80 per square foot, including surface preparation. When the entire surface from mud line to the top of the wall is coated on one side, the cost of initial coatings under conditions 1, 2, and 3 are as shown in Figure 25. The cost of initial coating adds only 5 percent to the installed cost of sheet-steel piling. The annual cost increment due to application of coating appears

Figure 25

COMPARISON BETWEEN ANNUAL COST OF CARBON STEEL BULKHEAD WITH INITIAL PROTECTION AND WITHOUT INITIAL PROTECTION

Condition 1	Surface Area Protected/lin.ft. (sq. ft.)	Protection Cost/lin.ft. ($)	Total Cost ($)	Est. Life (yrs.)	Annual Cost ($)
Carbon Steel with Coating	11.7	8.60	189	22-35	14.40-11.50
" " " Cath. Prot.		12.00	192	25-40	13.60-11.20
" " " Concrete Coping		20.00	200	20-30	16.10-13.00
" " " Combined Coating & Cath. Prot.		20.60	200	25-40	14.20-11.60
Carbon Steel			180	20-30	14.40-11.70
Condition 2					
Carbon Steel with Coating	22.1	16.60	270	22-35	20.50-16.50
" " " Cath. Prot.		12.00	265	25-40	18.80-15.40
" " " Concrete Coping		20.00	273	20-30	21.90-17.80
" " " Combined Coating & Cath. Prot.		28.60	282	25-40	20.70-16.40
Carbon Steel			253	20-30	20.30-16.50
Condition 3					
Carbon Steel with Coating	41.5	31.00	385	22-35	29.30-23.50
" " " Cath. Prot.		12.00	366	25-40	26.00-21.30
" " " Concrete Coping		20.00	374	20-30	30.00-24.30
" " " Combined Coating & Cath. Prot.		43.00	397	25-40	28.20-23.20
Carbon Steel			354	20-30	28.40-23.00

to be offset by a life extension of 2 years. If life can be extended by 5 or more years, initial installation coatings become cost effective.

In addition to cost advantages, there are other advantages to an initial coating for steel piling. Aesthetically, a coated surface looks better than a corroded surface. Also, maintenance may be confined to recoating areas where breaks in the initial coating occur, rather than coating and maintaining the entire surface. Finally, coatings may prevent or decrease the quantity of corrosion pits due to marine life, localized scouring, or dents.

Cathodic Protection

Provision for cathodic protection can be made at least cost during construction of a steel bulkhead. The installation may be as simple as an electrical connection between piles using reinforcing rods or as complex as a completely wired system with rectified alternating current and current sensing devices. In this report, a basic sacrificial system completely wired and with anodes in place is being considered. Such a system does not have to be connected at the time of installation; from an engineering standpoint it may be more advantageous to connect the leads to the anodes at a later date. A system of this type costs $10 to $15 per linear foot to install. The cost does not vary with the depth of water outside the wall, but with the size of the tidal and splash zones. It is in this area that electrical potential is developed and protection must be provided.

The extension of a steel bulkhead's life that is attributable to cathodic protection cannot be measured easily. If bulkhead failure occurs outside the electrolytic concentration zone, cathodic protection may not extend bulkhead life at all. If it is connected at bulkhead installation, the peak protection level may have passed before the corrosion rate peaks; if it is connected too late, it may not provide sufficient protection. A well designed and maintained system under normal circumstances can increase bulkhead life by 5 to 10 years. As shown in Figure 25, this period of life extension will justify the use of cathodic protection. Since the cost of installation does not vary with the length of piling, the economic advantage increases for protection of deeper piling.

It is difficult to generalize about the economics of cathodic protection because a system is usually designed to fit the environment factors at a particular location. If initial protection using sacrificial anodes is justified, replacement of these anodes at some future date may also be justified. When an unpressed current system is used, the annual electrical cost of the system must be included in economic analyses. Cathodic protection on berthing bulkheads may require periodic maintenance to replace leads and anode connections. The small initial cost in relation to the protection provided certainly calls for an economic evaluation on each new installation.

Concrete Coping

A well constructed, reinforced concrete cap on top of sheet-steel piling will endure as long as the piling. It becomes, therefore, not only an initial protection method but also a permanent protection method. The protection provided is in the top 2 to 3 feet of steel. If bulkhead failure occurred in this area, concrete coping would be demonstrated as an effective means of life extension. Such bulkhead failure, however, is rarely the case.

Concrete coping can be effective in supporting a structure built over a sheet-steel pile wall, in supporting adjacent structures, or in supporting facilities structurally tied into the bulkhead, such as a wharf or roadway. As shown in Figure 25, there is no economic advantage to concrete coping for the bulkhead alone, but when considered in the economic analysis of a group of dependent structures, it may be economically justifiable.

Other considerations may help to justify the use of concrete coping. Aesthetically, a copped bulkhead looks much better than a bulkhead corroding at the top. From a practical standpoint, it is far easier to work on, over, or near a capped structure than to work on, over, or near an exposed steel structure. The concrete also provides a level, strong foundation for adjacent structures.

Combinations of Initial Protection Methods

Coatings and cathodic protection appear to be initial protection methods that are cost effective in extending the life of carbon steel bulkheads. Can the combination of these two methods be equally cost effective? If the life extension estimates in Figure 25 are accurate, the answer to this question is no. The combination of protection systems increases the installation costs by more than 10 percent and, therefore, extends the payout period. It appears that the most cost effective use of initial protection systems is to determine where peak corrosion will take place and specify only that initial protection method which will retard corrosion in the most affected area.

C. Replacement System - Rip-Rap Sea Walls

Rip-rap bulk wall systems are one of the oldest and most effective means of shore stabilization. The bulk wall is constructed in layers of progressively larger stones from a point sufficiently below the mean low water level to prevent scour, up to the grade line on the shore side. The cover layer consists of large stones several hundred pounds in weight, which will resist the heaviest surf.

Some basic conditions must be met prior to the installation of rip-rap. The ocean floor under the rip-rap must be capable of supporting the heavy burden of the wall and should slope away gradually. Otherwise, the installation costs of the wall will increase geometrically, and stability of the wall may be more difficult to maintain. Rip-rap walls are not suitable for berthing of vessels, so there should be no need for access to the shore in the vicinity of the rip-rap.

The cost of rip-rap installation depends on these factors:

- cost of supporting bulkhead for shoreline;
- amount of stone used;
- availability of large stone;
- distance from shore to toe of wall; and
- accessibility to wall for heavy equipment.

With a supporting wall in place that is strong enough to support the additional lateral loading of the heavy equipment required to place rip-rap and with large stone available, rip-rap can be placed for $10 to $15 per cubic yard. As shown in Figure 26, rip-rap would be a very economical material for design condition 1. The annual cost of the rip-rap installation is only 15 to 20 percent of the annual cost of a replacement carbon steel bulkhead. A rip-rap bulk wall also appears to be economical for design condition 2. Installation costs may increase beyond the estimate in design condition 2 if the ocean bottom has to be prepared to support the weight of the wall or if proper placement becomes difficult at increasing depths. At some point between condition 2 and condition 3, rip-rap installation loses any annual cost advantage.

Figure 26

COMPARISON OF ANNUAL COST OF RIP-RAP SEA WALL
WITH A REPLACEMENT CARBON STEEL BULKHEAD

	Rip-Rap Wall Dimension		Cu. Yds. Rip-Rap Per Ft. of Wall (cu. yds.)	Cost Per Ft. of Wall ($)	Life Exten. (yrs.)	Annual Cost ($)
	Ht. at Wall (ft.)	Lgth. from Wall (ft.)				
Condition 1						
Rip-rap wall	8	15	2.7	35.0	20-30	*2.80-2.25
Carbon Steel				180.0	20-30	14.40-11.70
Condition 2						
Rip-rap wall	16	24	8.2	107.0	20-30	*8.50-7.00
Carbon Steel				240.0	20-30	19.20-15.60
Condition 3						
Rip-rap wall	31	44	27.0	350.0 450.0	20-30	*28.00-22.70 *36.00-29.20
Carbon Steel				354.0	20-30	28.40-23.00

* Some periodic maintenance is usually required to maintain the integrity of a rip-rap wall.

The advantages of rip-rap bulk walls are low cost installation and permanency. By using an existing wall as the facing, rip-rap can be placed quickly and inexpensively down to depths 10 to 12 feet below mean low water level. Some periodic maintenance, consisting of replacing some stone and filling void spaces to prevent wash-out, will produce a permanent wall.

Unfortunately, there are several limitations to the use of rip-rap. It cannot be used:

- where access to the beach from the sea is required;
- where the mud line slopes off sharply; or
- near a channel.

In addition, it becomes uneconomical in deep water, and its permanency becomes a disadvantage if replacement becomes necessary or construction is scheduled along the shore line. Unlike steel piling, the removal costs for rip-rap are high.

In summary, rip-rap is a very economical type of shore structure where shore protection is the major requirement. If berthing of ships is necessary or contemplated or if the function of the shore structure may change, it may not be suitable.

D. Repair Technique 1 - Concrete Reinforcing on the Shore Side

Repair technique 1 consists of placing a poured reinforced concrete wall behind the present bulkhead, while using the present steel bulkhead as an exterior form. The concrete extends below the maximum corrosion zone and is tied structurally to the bulkhead piling, wales, and tie-rods. Sound structural steel (75 percent of original cross-section) is required in the foundation piling, wales, and tie-rods. The type A section at NAS(NY) typifies this design (see Figure 27).

Actual cost data gathered at NAS(NY) indicates that the cost of this type of repair could approach $240 per linear foot or approximately 75 to 100 percent of the cost of new piling in the same location. A projection of the cost of this type of work over a longer section including both learning curve and quantity efficiencies, however, indicates that the cost may be lessened to approximately $150 to $200 per linear foot. Within this cost range, the repairs to the wall would have to prolong the life of the wall by 10 to 15 years to be economically justified (see Figure 28). If this repair technique provided a life extension of 20 years, it would be very cost effective.

There are several advantages to this type of repair procedure. First, the impervious concrete backing that is structurally tied to the sheet-steel wall prevents any openings or cracks in the wall from being widened by erosion or by backfill washing out from behind the wall. Also, the weakened areas do not necessarily increase the loading on adjacent piles, as they would without additional structural support. In addition, the task of withstanding the corrosive and erosive effects of tidal and surf action will gradually shift to the concrete as the steel corrodes. The structural integration of the steel piling foundation, the wales, tie-rods, and anchors, and the concrete wall should provide a strong impervious sea wall for several years. Finally, testing with this type of repair may permit some design modifications in the mass of concrete used and the depth of placement, which would, in turn, reduce the installation costs.

Analysis of the annual cost of this type of repair shows only nominal savings under condition 3 and additional expense

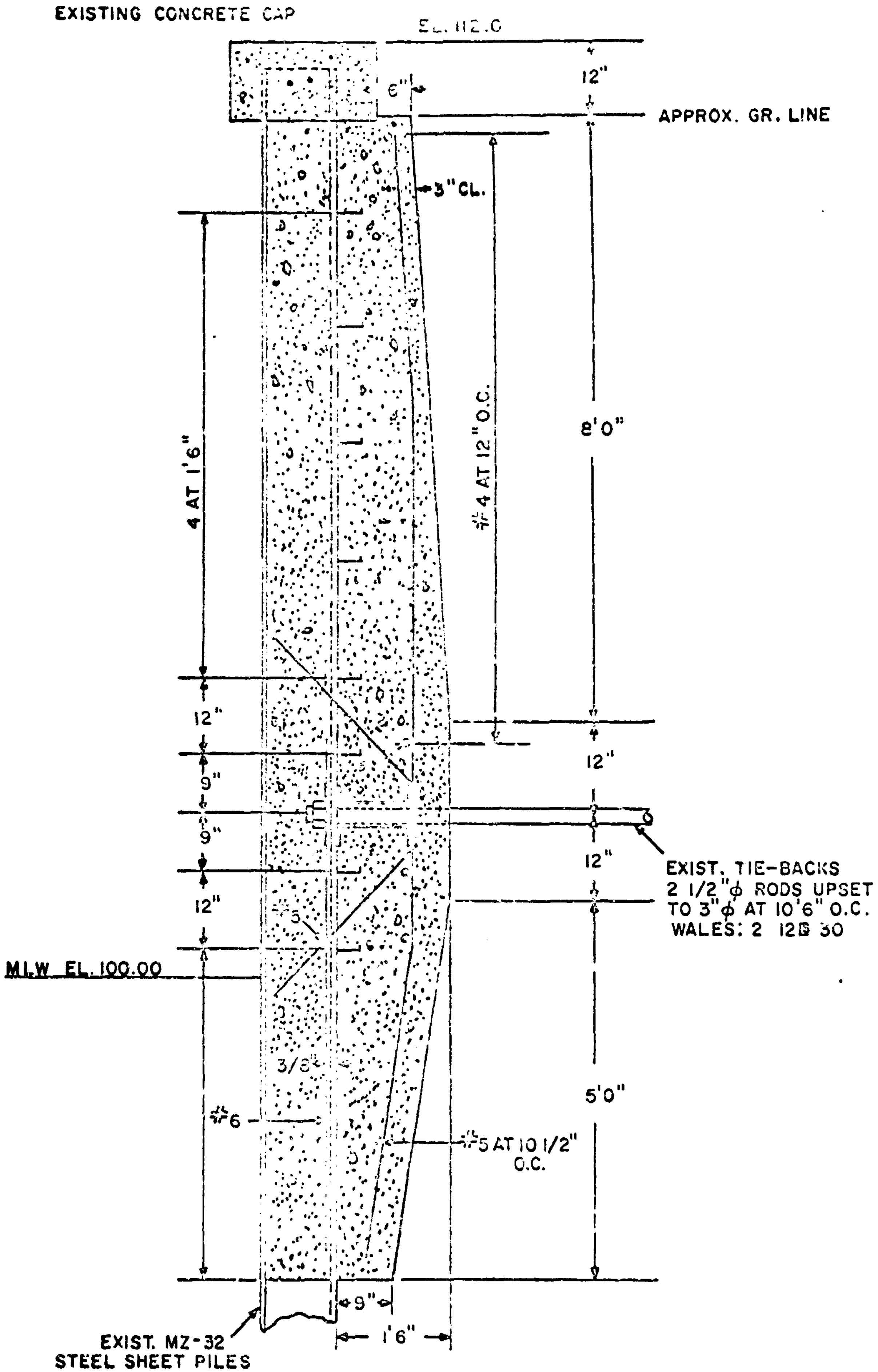


FIGURE 27 – ELEVATION SHOWING TYPE A REPAIRS

Figure 28

COMPARISON OF ANNUAL COST OF CONCRETE REINFORCING ON THE SHORE SIDE (TYPE A REPAIR) WITH A REPLACEMENT CARBON STEEL BULKHEAD

	Depth of Tie-Rods (ft.)	Depth of Concrete (ft.)	Cost Per Lin. Ft. ($)	Life Extension (yrs.)	Annual Cost ($)
Condition 1					
Type A Repair	10	12	150	15-20	14.40-12.00
Carbon Steel	10		180	20-30	14.40-11.70
Condition 2					
Type A Repair	10	16	200	10-20	25.90-16.00
Carbon Steel	10		240	20-30	19.20-15.60
			253	20-30	20.30-16.50
Condition 3					
Type A Repair	10	16	200	10-20	25.90-16.00
Carbon Steel	10		354	20-30	28.40-23.00
			373	20-30	30.00-24.30

under conditions 1 and 2. Unless the cost of installation can be markedly reduced or the life extension shown to be beyond estimates, this type of repair may have only marginal application. There is uncertainty about the design life of this technique, because there is no evidence of the effect of freezing and thawing cycles on this type of wall with a steel-concrete interface, or how well the concrete reinforcing, which will be partially exposed when the steel piling is eroded, can endure.

This type of repair is best suited to situations in which new piles cannot easily be driven, or the bulkhead to be replaced cannot easily be removed, but in which forming and pouring of concrete is possible. A sheet-steel pile bulkhead covered by a wharf or dock may be repaired using this technique. Similarly, a short section of piling wall can be repaired by this method without the use of expensive equipment.

E. Repair Technique 2 - Concrete Replacement of Steel in the Tidal Zone

Repair technique 2 utilizes the existing sheet-steel piling as a foundation for a poured, reinforced concrete wall that extends from below the tidal zone to the shoreline elevation. The existing steel structure is cut off at the mean water level line or slightly below. Then, forms and reinforcing are placed on either side of the old wall, and concrete is poured down to 2 or more feet below the mean low water level. The concrete is tied structurally to the remaining bulkhead piling, wales, and tie-rods. The type B section at NAS(NY) typifies this method (see Figure 29).

Experience with this type of construction at NAS(NY) showed a cost per linear foot of $268 in the test section (21 feet). With longer installations, the cost per linear foot should decrease to $175 to $250, even when the repairs are made to a wall in deep water. Life extension necessary to justify this cost would be in the 15- to 25-year range (see Figure 30). This life extension, which is more than that required in repair technique 1, can be expected because the repaired section will have a smooth concrete facing with no reinforcing exposed. With little overturning moment, such as in condition 1, the repaired wall should last as long as a poured concrete wall. In conditions 2 and 3, where additional weight at the top of the wall may add to the overturning moment, the structural condition of the steel piling below water will probably determine the life of the repaired wall. In all three conditions, a life expectancy equal to the original bulkhead may not be unreasonable.

The advantages of this type of repair are generally those of repair technique 1, with the exception that the concrete immediately assumes the burden of withstanding the environmental conditions. The structure will have a continuous finished face that would be architecturally pleasing and suited for berthing of small vessels. There is also the possibility of design modifications to reduce the cost of installation.

Unfortunately, the annual cost of this repair technique in conditions 1 and 2 compares marginally with a replacement

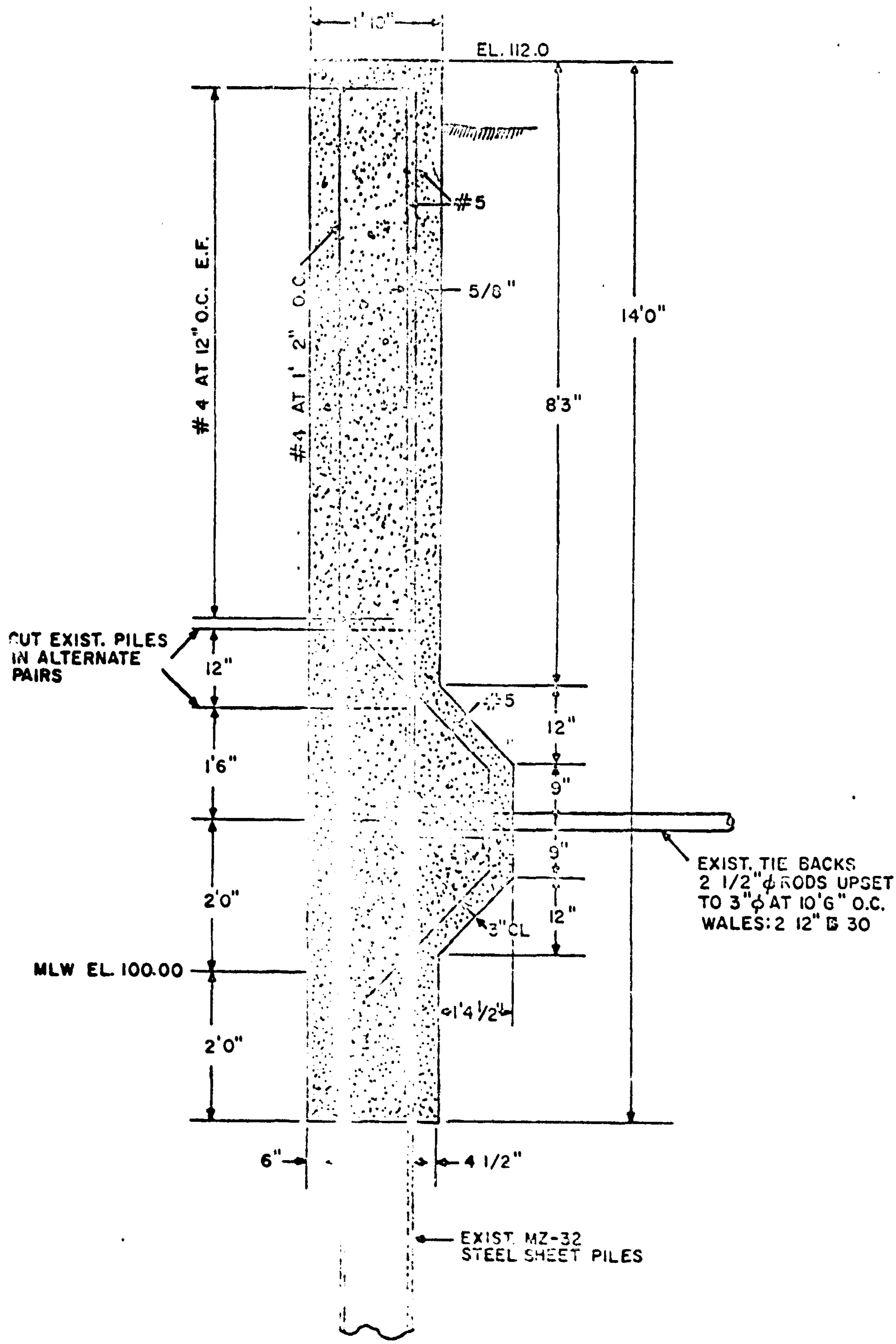


FIGURE 29 – ELEV... REPAIRS

Figure 30

COMPARISON OF ANNUAL COST OF CONCRETE REPLACEMENT OF STEEL TO BELOW MLW (TYPE B REPAIR) WITH A REPLACEMENT CARBON STEEL BULKHEAD

	Depth of Concrete (ft.) Shore	Depth of Concrete (ft.) Ocean	Cost Per Lin. Ft. ($)	Life Extension (Yrs.)	Annual Cost ($)
Condition 1					
Type B Repair	12	12	175	25-30	12.40-11.40
Carbon Steel			180	20-30	14.40-11.70
Condition 2					
Type B Repair	14	12	225	15-25	21.60-15.90
Carbon Steel			240	20-30	19.20-15.60
			253	20-30	20.30-16.50
Condition 3					
Type B Repair	16	12	250	15-25	24.00-17.70
Carbon Steel			354	20-30	28.30-23.00
			373	20-30	30.00-24.30

wall of carbon steel (see Figure 30). Unless the cost per linear foot can be reduced considerably, the application of this technique in shallow water is limited. In condition 3 there appears to be a favorable cost comparison between this repair technique and replacement with carbon steel.

Repair technique 2 results in a poured concrete wall in and above the tidal zone, which is structurally tied to the sheet-steel piling foundation. Since the top of the steel section is removed, the finished wall will be an attractive sea wall suitable for berthing purposes. This technique does not appear to be economical for use in shallow water, but it may be used in bulkheads adjacent to channels or in bulkheads that are part of, or adjacent to, wharfs.

F. Repair Technique 3 - Composite Wall with Timber, Concrete, and Steel

Repair technique 3 results in a composite wall with structurally integrated layers of timber, concrete, and steel. A timber-sheeting wall is driven into the mud line a minimum distance of 6 inches from the existing sheet-steel bulkhead. The timber and steel walls are bolted together and reinforcing for the concrete is placed between the two walls. The space between the timber and steel is filled with concrete. This technique is similar to the type C construction at NAS(NY). At the Naval Air Station, however, the timber was driven next to the wall, and only the cells formed by the piling were filled with concrete.

The cost of this type of repair will vary with the length of timber sheeting that is driven and the depth of the poured concrete. The cost to drive creosoted timber piling up to 40 feet in length is approximately $400 to $500 per 1,000 board feet. Concrete cast-in-place costs $15 to $20 per cubic yard. Using these cost estimates as a guide, the cost of repair technique 3 in the three conditions is estimated at $69 per linear foot, $156 per linear foot, and $343 per linear foot. (Type C construction at NAS(NY) cost $68 per linear foot in an area similar to condition 2.)

Not only do costs increase sharply in deep water, but the results are less reliable. Concrete can be cast into shallow water with good results, but the results are at best uncertain when concrete must be cast into deep water. A coffer dam should be used in deep water, which sharply increases the cost. Primarily for this reason, the life extension estimates should be shorter in deep water conditions.

Figure 31 shows the annual cost estimates for repair technique 3 and the comparable annual cost of a replacement carbon steel bulkhead. As shown, repair technique 3 appears to be very cost effective in tidal installations, marginally cost effective in shallow water, and cost ineffective in deep water.

There are several advantages to this type of repair that cannot be measured economically. The timber facing is

Figure 31

COMPARISON OF ANNUAL COST OF COMPOSITE WALL WITH TIMBER, CONCRETE, AND STEEL WITH A REPLACEMENT CARBON STEEL BULKHEAD

	Timber Sheeting Length (ft.)	Depth of Concrete (ft.)	Minimum Thickness of Concrete (in.)	Cost Per Lin. Ft. ($)	Life Extension (yrs.)	Annual Cost ($)
Condition 1						
Composite Repair	14	9	6	69	15-20	6.60-5.50
Carbon Steel				180	20-30	14.40-11.10
Condition 2						
Composite Repair	22	17	8	156	10-20	20.50-12.50
Carbon Steel				240 253	20-30 20-30	19.20-15.60 20.30-16.40
Condition 3						
Composite Repair	42	32	.12	343	10-20	[illegible]4.40-27.50
Carbon Steel				354 373	20-30 20-30	28.30-23.00 29.90-24.30

resilient and can withstand shock and alternate wetting and drying better than concrete or steel. The concrete is partially protected from freezing and thawing cycles and in turn protects the previously exposed surface of the steel. The timber exterior is a good bulkhead material for use where ships are berthing. The concrete extends down to the silt line and does not contribute to the overturning moment of the wall as it may in repair techniques 1 and 2.

A major disadvantage of this repair technique is that it is of questionable value in deep water. Also, the concrete and timber facing are structurally tied to the steel bulkhead only and are not tied to the anchoring system.

G. Maintenance Technique 1 - Coating Application

Tests conducted by the U.S. Naval Civil Engineering Laboratory and the Port of New York Authority demonstrate that an impermeable layer of good coating material can be applied both before installation and while the piling is in service. The test results also indicate that most coatings will break down in 2 to 5 years in service but that the failure condition is localized. With these results in mind, it appears that periodic maintenance to maintain an impermeable coating of corrosion-proof material can extend life within justifiable cost limitations.

The major limitation to wide usage of protective coatings is the relatively high cost of in situ application. As discussed in Section IV, all coatings must be placed over a clean adherent surface. Before piling is driven, the lengths of piling can be peened or sandblasted to white metal and the coating can be brushed on easily. Once the pile is driven, however, coating the exterior surface is difficult. The pile surface is relatively inaccessible, usually wet or damp, and it may be covered with scale or vegetation. The blasting, cleaning, and application in and above the tidal zone can be done from a platform hung over the side of the bulkhead. Work under the tidal zone must be done by divers.

The cost of coating applications prior to installation varies from $.35 to $.80 per square foot. The cost of coating applications on in situ piling varies from $1.00 to $2.00 per square foot in the tidal zone and from $3.50 to $8.00 per square foot under water. A complete coating application for a bulkhead with 6 to 12 feet of tidal and splash zones and 2 to 3 feet of surface in the active electrolytic zone may cost $30.00 to $50.00 per linear foot.

Figure 32 indicates the conditions necessary to optimize annual savings through periodic applications of coatings. Coatings applied on short intervals, such as 2 years, may provide additional bulkhead life, but they will not be cost effective, even if a small area is treated. With 5-year intervals between coating applications, this type of periodic maintenance may be cost effective, especially if small areas (5 to 10 square feet per linear foot of wall) are treated.

Figure 32

ANNUAL COST ANALYSIS OF PERIODIC APPLICATIONS OF COATINGS ON SHEET-STEEL BULKHEADS

Time Interval Between Coating Applications (yrs.)	Area Covered Per Linear Foot of Bulkhead (sq. ft.)	Cost of Coating Per Lin. Ft. of Bulkhead ($)	Annual Cost Increase for Life Extension of			Annual Cost Saving for Extended Life of Bulkhead*		
			5 yrs. ($)	10 yrs. ($)	15 yrs. ($)	5 yrs. ($)	10 yrs. ($)	15 yrs. ($)
2	**5	7.50	3.54	3.62	4.02	1.77	2.97	3.78
	**10	15.00	7.08	7.24	8.04	1.77	2.97	3.78
	***15	35.00	16.50	16.90	18.80	1.77	2.97	3.78
5	5	7.50	1.25	1.27	1.30	1.77	2.97	3.78
	10	15.00	2.50	2.54	2.60	1.77	2.97	3.78
	15	35.00	5.83	5.92	6.08	1.77	2.97	3.78
8	5	7.50	0.71	0.76	0.72	1.77	2.97	3.78
	10	15.00	1.42	1.52	1.44	1.77	2.97	3.78
	15	35.00	3.32	3.55	3.47	1.77	2.97	3.78

*Bulkhead installation cost assumed to be $300/lin. ft. Life without protection is 25 years.

**Coating in splash zone only.

***Coating in splash zone and active electrolytic zone.

Applications of coatings over the entire tidal and active electrolytic zones can be justified when done at 8-year intervals.

To determine the best policy for coating applications, it is necessary to integrate the functional life of the coating in the design environment and the cost effectiveness of periodic applications. If used in combination with cathodic protection, coating applications may be limited to the tidal and splash zones. Once again, the effectiveness of corrosion retardation and the cost effectiveness of periodic coating must be compared to increased bulkhead life to determine the best course of action.

There are other advantages to coating systems for maintenance work. They do not change the basic shape or appearance of the bulkhead. The work can be done sporadically by a small crew under Public Works Office administration. Technical advances can be easily incorporated. Of greatest importance is the fact that a good coating application can almost completely arrest corrosion during the period of maximum effectiveness.

H. Maintenance Technique 2 - Grouting and Concrete Patching

Properly installed, sheet-steel piling is only semi-impervious to penetration by sea water. After considerable exposure, penetration increases due to puncture, bolt holes, and joints that have loosened, and corrosion-induced holes. When holes and leaks occur, the corrosion and erosion processes increase because fill is washed out from behind the wall and corrosion proceeds on both surfaces of the wall. When holes and leaks occur, proper sealing and/or soil stabilization to prevent sea water from washing out backfill can result in longer wall life. Two related methods that may be used to seal leaks and stabilize soil are cementitious grouting and concrete patching. These methods are complementary, with the method selected for use based on the type of hole and the soil conditions.

Grouting is the process of forcing cementitious materials into the earth in an effort to bind the soil into a hard mass. A pipe is driven down into the soil and grout, under pressure, is forced down the pipe. The grout will seek out the voids and least-compacted soil and will eventually bond soil particles together. In highly compacted soil or gravel, grout can be very effective. It is not very effective in sandy soil or in loosely compacted material, and will exit quickly through a large hole.

Concrete patching is the process of compacting concrete into a prepared or natural void. In bulkhead repair, it can be done by excavating on the shore side of the wall and pouring in the concrete. Patching can be done from the sea side by opening a cavity large enough to provide bulkhead steel support on all sides of the hole and pumping concrete in through a form built on the outside surface of the wall (similar to the type D construction at NAS(NY)).

The cost of grouting depends on the size and depth of areas that must be filled and the type of soil. A grouting crew consists of 6 to 10 men, and they can grout 16 to 40 small areas in a day. Unless there is sufficient work to provide a full day's work, the cost becomes high in relation to the work performed. Concrete patching, on the other hand,

can be done by 1 to 2 men who can patch 4 to 10 holes per day. The experience at NAS(NY) indicates that a cost of $15.00 to $30.00 per hole is reasonable.

With such limited data available, it is difficult to establish a cost per linear foot or a life extension figure. It is reasonable to assume, however, that grouting or patching every 3 to 5 years can be done for less than $800 to $1,500 per 100-foot section and will extend life by at least 5 years. This expense would be justified on a wall that normally would last 25 years.

The advantages of grouting and patching are the flexibility in time and equipment for performance of the work, the low investment, and the low skill factor involved. These methods are typical maintenance department projects which can be grouped together and scheduled conveniently. A disadvantage is the difficulty in assessing the value of the work done. Another disadvantage is that neither method can be performed inexpensively on holes below mean low water on the sea side or at considerable depths on the shore side of the bulkhead.

I. Guidelines for Use of Replacement, Repair, and Maintenance Systems

A number of factors must be considered when a sheet-steel pile bulkhead has to be repaired or replaced. The technical limitations of methods and materials, the economic constraints, the environment and topography of the shoreline, and the utilization of the shoreline, all have a bearing on the choice of the best technique. Some general conclusions can be drawn, however, and they are summarized in Figure 33.

Rip-rap is the least expensive shore protection where the shoreline is shallow and where access to the shore is unnecessary. If the shoreline is shallow, and it is used frequently and maintenance facilities are available, repair technique 3 is desirable. In deeper water, repair techniques 1 and and 2 and special steel become desirable. A carbon steel replacement with cathodic protection or coating may be desirable if the life extension is sufficient to meet mission life. When mission life is uncertain, the lowest investment, plus the best annual cost, point to repair techniques 1 and 3.

It is difficult to generalize about the selection of maintenance techniques and maintenance cycling. Knowledge and experience in the area are the best guide in deciding how important the environmental factors will be and how effective coating materials and grouting have been. After a maintenance method has been selected and scheduled, the bulkhead should be inspected often to determine if a change in policy is necessary.

Figure 33

GUIDELINES FOR SELECTION OF REPAIR OR REPLACEMENT SYSTEMS

	Condition 1 Shoreline in Tidal Zone	Condition 2 Shoreline Below MLW	Condition 3 Deep Water on Outside of Wall
Where shoreline is not used	rip-rap ($2.50)	rip-rap ($7.75)	Repair Tech 1 or 2 ($21.00)
Where shoreline is used	Repair Tech 3 ($6.00)	Repair Tech 3 or Special Steel ($13.80)	Carbon Steel with Cathodic Prot. Repair Tech 1 or 2, or Special Steel ($21.00)
Where mission life is uncertain, or where replacement funds are unavailable	Repair Tech 3 ($6.00)	Repair Tech 3 ($13.80)	Repair Tech 1 or 2 ($21.00)
Where mission life is certain	Repair Tech 3 ($6.00)	Repair Tech 3 or Special Steel ($13.80)	Special Steel with Cathodic Prot. ($21.00)
Where maintenance is difficult to do	Special Steel or Repair Tech 2 ($11.60)	Special Steel or Repair Tech 2 ($15.40)	Special Steel ($22.90)

Note: Figures in parentheses are approximate annual cost for bulkhead repair or replacement.

IX. ANALYSIS OF REPAIR WORK AT THE NAVAL AIR STATION, NEW YORK

The bulkhead at the southeast corner of the Naval Air Station, New York, is a typical illustration of a facility approaching the end of its functional life. This bulkhead has been in place since 1942 and has had no appreciable maintenance since that time. In one section, the piling web at the top of the wall is completely eroded. In other sections, there are large holes just above and below the mean low water line, allowing erosion of backfill material. A heavy coating of scale covers the entire length and depth of the bulkhead on the exposed side. There are also some areas in which the bolts joining the tie-rods to the bulkhead have pulled loose. Although the bulkhead is in no immediate danger of actual structural failure, it should be repaired or replaced in the near future to prevent additional loss of backfill and to arrest further structural deterioration.

A. Environmental Factors

Before an analysis of the cost of various repair and replacement techniques could be made, the bulkhead's environment had to be examined. A study of the climatic, tidal, biological, and electrical features of the area indicated that there were no unusual design conditions to be considered. There are no prevailing winds which might accentuate normal surf and wave conditions in the adjacent waters. The Rockaway Beach Peninsula stands between the bulkhead and the open sea and blunts the effect of storm winds from the southeast. The tidal flow runs roughly parallel to the bulkhead. Except for the area between the ramp and the wharf, the water is not deep and there is little evidence of scouring along the mud line.

Because of the porosity of the soil and the flatness of the terrain, excavations in this area revealed little ground water down to the mean high water level. There appears to be substantial rain runoff, however, from the seaplane apron and runway adjacent to the seaplane ramp. This runoff seems

to flow down behind the wall in the section between stations 13 + 40 and 21 + 17. This runoff probably accelerates corrosion on the inside of the wall and contributes to the washing of backfill through holes in the bulkhead in this area.

Pollution is not a major problem. Because of the relative cleanliness of the water, the shallowness of the bay, and the subsequently higher water temperature, conditions could be satisfactory for infestation of marine borers. These conditions may be a deterrent to the use of timber in this area.

There is no evidence of the existence of high electrical potential in the soil adjacent to the wall.

Heavy scale and the complete erosion of the webbing at the top of the wall are factors in the selection of a repair or maintenance method. A substantial amount of work will be necessary to prepare the surfaces of the wall for any bonded coating or repair material such as concrete.

The physical environment of the bulkhead appears normal, but the economic environment is difficult to ascertain. The base is used as a reserve pilot training station. Expansion to a broader mission status may be hampered by the proximity of deep water, roads and bridges, and the Kennedy International Airport. The mission life of the bulkhead is dependent on the mission life of the base. The bulkhead is one of the less vital elements in the operation of the base and, with the exception of the section of the bulkhead built into the tanker wharf and the adjacent section which supports a roadway and parking apron, the cost-of-failure is not an important consideration. The bulkhead in the vicinity of the tanker wharf, however, should be maintained in excellent condition. Any failure in this area could jeopardize the fuel supply lines for the base. The economic factors in the repair or replacement of this section, therefore, may be outweighed by the necessity of keeping the wharf in operating condition.

In summary, the environmental factors do not appear to influence the choice of repair or replacement procedures except for the uncertainty concerning the mission life of the bulkhead and the need to maintain the structure in the vicinity

of the tanker wharf. Without environmental constraints, the decision between repair or replacement can be made on a cost versus life basis. With the constraint of mission life uncertainty, the most economical repair or replacement procedure will be that having the lowest initial cost.

B. Analysis of Repair Work Performed

The repair techniques previously mentioned offered the prospect of additional bulkhead lifetime at a lower installation cost than a replacement steel bulkhead. For this reason, several repair techniques were considered and four were used in the experimental repair program at NAS(NY): type A, concrete reinforcing on the shore side; type B, concrete replacement of steel in the tidal zone; type C, timber sheet facing with concrete filler; and type D, concrete patching. Each technique was applied on a 21-foot section of bulkhead. Type B and D repairs were made on sections of the wall where the water on the sea side was shallow; type A and C repairs were made in sections where the water line was further below mean low water. Type D work will be considered as a maintenance technique since it does not change the form or structural function of the bulkhead.

Type A Repair

Type A repair, shown in elevation in Figure 27, was made on a section adjacent to the tanker wharf. The repairs were made in 17 working days despite some unexpected difficulties in patching existing holes and removing old piles. A breakdown of the construction sequence used, along with man and machine hours, is shown in Figure 34. The most time-consuming stages in type A repair were:

. clearing and excavation;
. driving sheeting and wellpoints;
. form construction; and
. reinforcing.

The contractor performed this work in a manner that would be inefficient for longer lengths of wall. He stationed the crane in one location and swung the boom of the crane in an arc of 90° during excavation. Forms and reinforcing were cut to length and assembled on the site. Repairs on a longer

Figure 34

CONSTRUCTION SEQUENCE - TYPE A REPAIR

Stage	Man-Hours Worked	Equipment Hours			
		Crane	Dozer	Compressor	Pumps
1. Clear and Excavate	71	15			6
2. Drive Sheeting and Wallpoints	134	2		8	89
3. Patch Holes	36	1			
4. Chipped Scale	10			10	
5. Reinforcing	57			23	
6. Forms	70				
7. Concrete	32			2	
8. Remove Forms and Sheeting	34	4			
9. Backfill	49		6		
Total	493	22	6	43	95

wall should be made in a continuous sequence. The crane should travel parallel to the wall to minimize boom travel. Reinforcing and form materials should be precut and prefabricated when possible. Forms should be reused. Using these techniques, the cost of type A repair could be reduced 20 to 25 percent.

With the techniques used, the cost per linear foot was $239 (see Figure 35 for breakdown). Seventy percent of the total cost before overhead was due to labor costs, and it is in this area that cost efficiencies can be realized. This project was so limited that great flexibility was required of the work force. On a longer wall, a man could perform one task, such as descaling, for several days and become more effective in that task. In contrast, the informality of supervision and cooperation between personnel may be harder to achieve on larger projects. The only material savings that would probably result from larger projects would be savings in lumber from the reuse of forms.

It is reasonable to conclude that type A repair could be done over long lengths of bulkhead for $150 to $200 per linear foot. Even lower costs could be reached if the depth of concrete below the wales on the shore side could be reduced. Excavation, form construction, and reinforcing in the area from the wales down to the required concrete depth are very expensive in relation to the same work done above the wales. If this depth of concrete can be reduced, additional savings of $20 or more per linear foot can be realized.

<u>Type B Repair</u>

Type B repair, shown in elevation in Figure 29, was made on a section between the tanker wharf and the Coast Guard ramp. The construction sequence for type B repair is shown in Figure 36. As shown, the most time consuming and therefore the most expensive stages were:

- excavation on the shore side;
- welding and placement of reinforcing;
- inside form construction; and
- concrete placement.

All of these stages could be completed at a lower cost per linear foot of wall if the work area included a longer wall. By moving the crane parallel to the wall, the earth

Figure 35

COST SUMMARY FOR TYPE A REPAIR

A. Labor Expended

Category	Hours	Rate	Cost	
Laborer	145	$4.65	$ 674	
Crane Operator	93	6.30	586	
Oiler	17	3.50	60	
Dock Builder	135	5.80	782	
Foreman	103	7.00	721	
	493		2,823	$2,823

B. Equipment Used

Category	Hours	Rate	Cost	
Crane	22	$10.00	$220	
Bulldozer	6	6.30	38	
Compressor	43	1.50	65	
Wellpoints	95	3.00	185	
			488	488

C. Material Used

Material	Amount	Cost	Total	
Plywood (3/4")	420 sq.ft.	$.25	$105	
Studs (3x6)	300 ft.	.13	39	
Reinforcing	848 lbs.	.09	76	
Concrete	26 c.y.	17.50	455	
Calrock	5 gals.	3.00	15	
Cement	2 bags	1.50	3	
			693	693

D.	Total Cost without Overhead and Profit	$4,004
E.	Total Cost with Overhead and Profit (25%)	$5,005
F.	Cost per Linear Foot of Wall	$ 239

Figure 36

CONSTRUCTION SEQUENCE - TYPE B REPAIR

Stage	Man-Hours Work	Equipment Hours Crane	Dozer	Compressor	Pumps
1. Move equipment in	12				
2. Excavation (seaside)	12	3			
3. Excavation (shoreside)	125	24	1		13
4. Remove wall	48			1	
5. Outside form construction	23	1			
6. Reinforcing	85			40	
7. Inside form construction	124	4			
8. Form ties	64				
9. Draining forms	10			3	115
10. Place concrete	54	5			
11. Remove forms and backfill	15	3	5		
12. Clean site and finish wall	18				
Total	590	40	6	44	128

excavated would be moved a shorter distance and the crane would not have to be repositioned as often as it was. The reinforcing could be placed in longer sections. Prefabricated forms could be stripped off completed sections and moved to the next length of wall to be repaired. Several sections of concrete could be poured at one time. Using these or similar techniques, it is estimated that the actual cost of type B repair, i.e., $268 per linear foot (see Figure 37) could be reduced by 15 to 20 percent.

The contractor performed the type B repair before other repair techniques were attempted. He tried to drain the area inside the wall but below the tidal zone with two pumps. This draining technique proved unsatisfactory and resulted in delay during the excavation, form construction, and concrete placement stages. As a result of this experience, he used a well point system on the type A repair. Some cost reductions would have resulted from using a well point system during type B repairs.

Material savings resulting from type B repair over long lengths of bulkhead would be limited to timber usage. By reusing forms, a small cost saving may be achieved. As discussed under type A repair, design changes which would result in less concrete below the wales would lower the cost of this repair technique.

This type of repair calls for concrete on the ocean side down to a depth of 2 feet below mean low water. At the location where this work was performed, the mud line was above mean low water, which meant that excavation in front of the wall was necessary to facilitate the placement of forms. Where the mud line is more than 2 feet below mean low water, a counterweight outrigger beam may have to be installed to support the weight of the concrete wall while the concrete is in a plastic state. It is assumed that the construction cost would not vary greatly between excavation and placement of a support beam. If the mud line elevation is such that the exterior form can be placed on the shore, however, some construction cost savings may result.

In summary, type B repairs may be made for $175 to $250 per linear foot over long lengths of wall. Some possibility of lower costs exists if the amount of concrete placed below the wale can be reduced.

Figure 37

COST SUMMARY FOR TYPE B REPAIR

A. Labor Expended

Category	Hours	Rate	Cost	
Laborer	207	$4.65	$ 959	
Crane Operator	71	6.30	447	
Oiler	69	3.50	241	
Dock Builder	162	5.80	940	
Foreman	81	7.00	567	
	590		3,154	$3,154

B. Equipment Used

Category	Hours	Rate	Cost	
Crane	40	$10.00	$400	
Bulldozer	6	6.30	38	
Compressor	44	1.50	66	
Pumps	128	.40	51	
			555	555

C. Materials Used

Material	Amount	Cost	Total	
Plywood (3/4")	650 sq.ft.	$.25	$162	
Studs (2x6)	620 ft.	.13	81	
Reinforcing	800 lbs.	.09	72	
Concrete	26 c.y.	17.50	455	
Gravel	2 c.y.	5.00	10	
Calrock	1 gal.	3.00	3	
Epoxy	1 gal.	13.00	13	
			796	796

D.	Total Cost without Overhead and Profit	$4,505
E.	Total Cost with Overhead and Profit (25%)	$5,631
F.	Cost per Linear Foot of Wall	$268

Type C Repair

Type C repair work at the New York Naval Air Station was performed between the tanker wharf and the seaplane ramp in an area where the water depth in front of the wall was 15 to 20 feet. The work was performed in five working days and consisted of three stages:

- assembly of the timber facing on shore;
- placement of the facing against the steel bulkhead; and
- filling the open cell areas between the timber and steel with concrete.

The repair work was performed in a most efficient manner but did not produce the type of repair that was specified. According to specifications, the timbers were to be individually driven and sprung into the wall. Then the timbers were to be joined into a composite facing and bolted to the wall (see Figure 38). The timbers could not be driven to the specified elevation because the mud line was below this elevation. As a result, the timbers were assembled on shore and dropped into place as a unit. In contrast to type A and B repairs, type C repair would cost more over a longer length of wall if the installation was done properly. The actual cost of $68 per linear foot (see Figure 39) could increase to $100 to $150 per linear foot if each pile were driven separately.

Type D Maintenance

Type D maintenance was performed on the bulkhead adjacent to the seaplane ramp. Twenty-one holes were selected for maintenance and some fill behind each hole was removed to provide room for a concrete patch. The metal surrounding the hole was cleaned to provide a good bonding surface for concrete and epoxy. Then, the holes were filled with concrete up to the steel piling surface and an exterior layer of epoxy was applied (see Figure 40).

The cost of type D maintenance is a function of the size and location of the holes. The holes on which maintenance was

GRAPHIC NOT REPRODUCIBLE

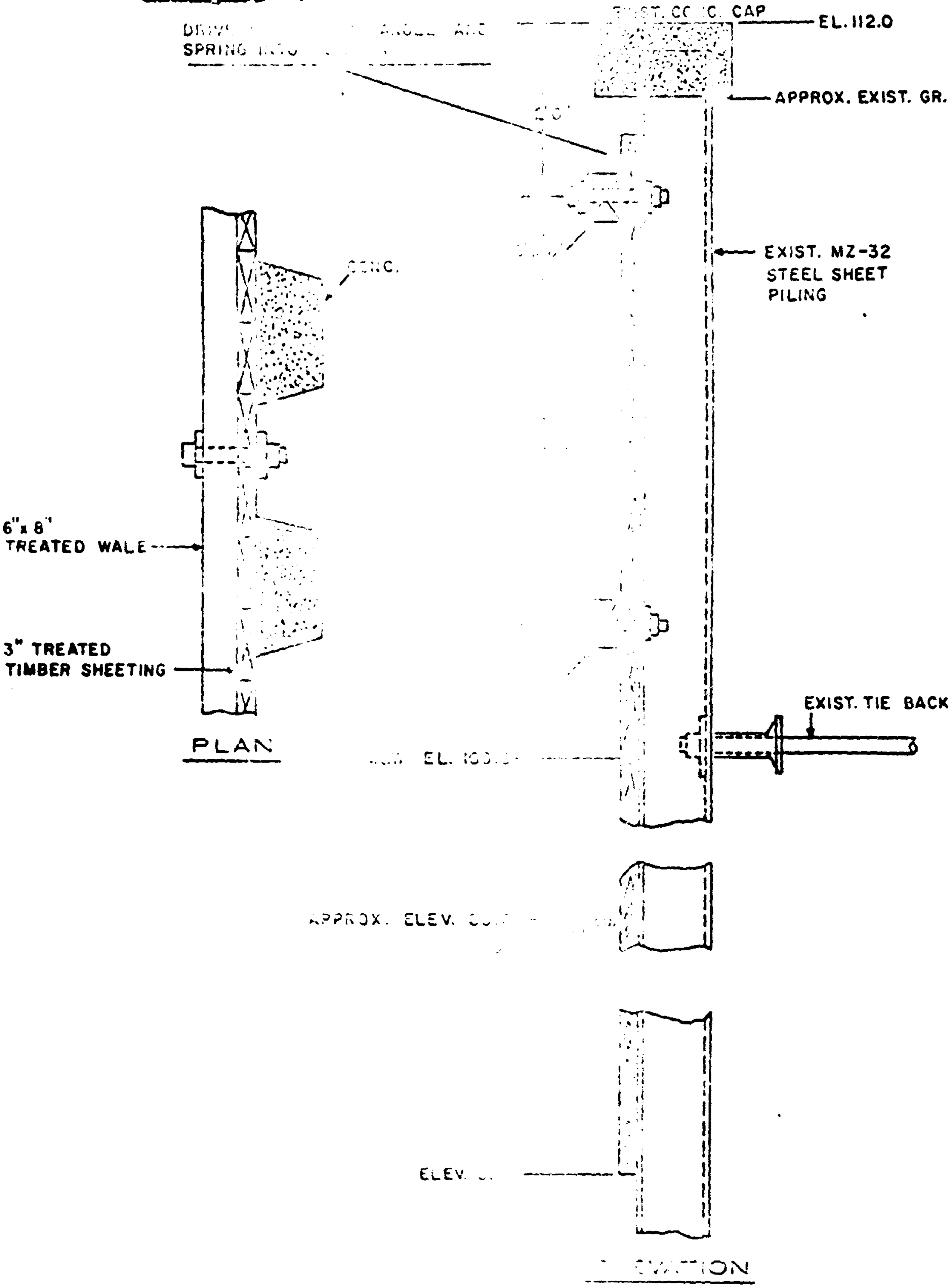


FIGURE 36 – [illegible] TYPE C REPAIRS

Figure 39

COST SUMMARY FOR TYPE C REPAIR

A. **Labor Expended**

Category	Hours	Rate	Cost	
Laborer	19	$4.65	$ 88	
Crane Operator	27	6.30	170	
Oiler	20	3.50	70	
Dock Builder	29	5.80	168	
Foreman	25	7.00	175	
	120		671	$ 671

B. **Equipment Used**

Category	Hours	Rate	Cost	
Crane	7	$10.00	$70	
Bulldozer	1	6.30	6	
Compressor	5	1.50	8	
			84	84

C. **Materials Used**

Material	Amount	Cost	Total	
Timber (3")	1,240 ft.	$ .21	$261	
Timber (6")	42 ft.	.50	21	
Concrete	6 c.y.	17.50	105	
			387	387

D.	Total Cost without Overhead and Profit	$1,142
E.	Total Cost with Overhead and Profit (25%)	$1,427
F.	Cost per Linear Foot of Wall	$68

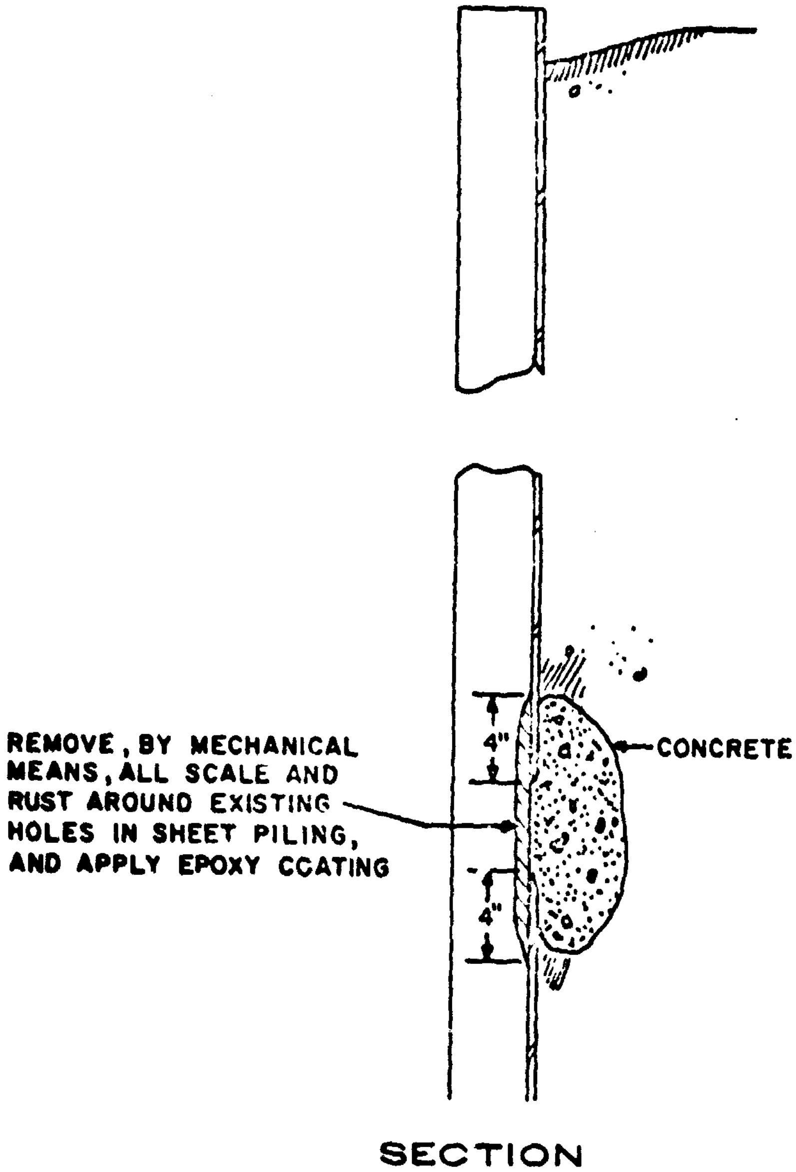


FIGURE 40 —ELEVATION SHOWING TYPE D MAINTENANCE

performed at the New York Naval Air Station were in the web section of the piling at the elevation of the wales (approximately mean water level). Work had to be done at low tide in water depths of 0 to 3 feet. The cost of this maintenance work was $14 per hole (see Figure 41). Since the holes appeared in adjoining web sections, the work was done on 21 piles over a 40-foot length at a cost of $7.50 per linear foot of bulkhead.

It is difficult to project how the cost of concrete patching will vary without observing more work. The cost will vary with the number, size, and location of the holes rather than the length of wall to be repaired. It does not seem that major cost savings can be assumed for work on a longer wall. Concrete patching is not skilled work and repetition may not result in greatly increased work efficiency.

C. Summary and Recommendations

The experimental repair projects at the New York Naval Air Station offered the opportunity to test repair procedures in a typical bulkhead environment. The test projects also provided an opportunity to gather cost data on repair procedures. Unlike the cost of replacement and maintenance techniques, the cost of many of the suggested repair techniques has not been adequately documented.

The tests did show that functional repair work can be done on steel bulkheads. The condition of the remaining steel was more than adequate to support the placement of new bulkhead materials. In addition, the cost data indicates that repairs can be made within the cost range estimated by the Eastern Division of the Naval Facilities Engineering Command. Although the actual costs were higher than estimated, there are several procedural improvements which can be instituted in projects involving longer lengths of bulkhead that will reduce the cost per linear foot. Finally, the tests indicated that the repaired bulkhead was structurally adequate to fulfill its function for several years after the end of life of the original bulkhead.

Type A repairs actually cost $239 per linear foot; the estimate for this type of repair was approximately $150 per

Figure 41

COST SUMMARY FOR TYPE D MAINTENANCE

A. Labor Expended

Category	Hours	Rate	Cost	
Laborer	4	$4.65	$ 19	
Crane Operator	4	6.30	25	
Oiler	4	3.50	14	
Foreman	8	7.00	56	
			114	$114

B. Equipment Used

Crane	3	$10.00	$30	30

C. Materials Used

Concrete	4 c.y.	$17.50	$70	
Epoxy	2 gals.	13.00	26	
			96	96

D. Total Cost without Overhead and Profit	$240
E. Total Cost with Overhead and Profit (25%)	$300
F. Cost per Linear Foot of Wall	$7.50

linear foot. With procedural improvements and more efficient use of materials, however, it is now possible to estimate a cost of $150 to $200 per linear foot for this type of repair. Type A repairs can be justified by a life extension of 10 to 15 years when the alternative is replacement with carbon steel. These repairs are best suited for use in areas where repairs are difficult to make and where access to the front face of the existing bulkhead is difficult. This technique may be best for repairs under and adjacent to the wharf and seaplane ramp.

Type B repairs cost $268 per linear foot at the Naval Air Station, New York. The estimate of $150 to $175 per linear foot proved to be low even with anticipated improvements in construction procedures. Repairs of this type can be justified by a life extension of 15 to 20 years if compared with a carbon steel replacement bulkhead. Type B repairs may be suited to renovation of a bulkhead if the appearance of the structure is important and if the wall may be used for berthing ships. There are no sections of the bulkhead at the Naval Air Station in New York for which this technique is ideally suited.

Since type C repairs were not made in accordance with the design specifications, it is difficult to project the actual cost of this type of repair. The cost should not exceed $150 per linear foot, however, and could be justified by a 10 to 15 year life extension. The cost and efficacy of this type of repair depends on the depth to which the timber facing must be driven. When the mud line is less than 15 feet from the top of the bulkhead and when the depth of water is less than 2 feet at low tide, this type of repair can be done inexpensively and can be expected to provide a long life extension for the bulkhead. Type C repairs (or repair technique 3, discussed in Section VIII) are best suited for use on shallow water bulkheads, such as the section between the Rockaway Bridge and the seaplane ramp, or the section between the tanker wharf and the Coast Guard area at the New York Naval Air Station.

Type D repairs (described in Section VIII as concrete patching) cost only $10 to $20 per hole. While it is effective in suppressing erosion in the area of the patch, it may

not extend the functional life of the bulkhead by any measurable period. In addition, if patching is required on a yearly basis, it may prove to be a very expensive maintenance technique. This type of maintenance is best suited to conditions in which mission life is uncertain and the cost-of-failure of the bulkhead is low.

X. PROMISING RESEARCH AND DEVELOPMENT AREAS

In the previous discussions of installation, maintenance, and repair possibilities for shore protection structures, the state of the art has been a limiting factor in several cases. The following brief paragraphs describe some of these present technological limitations and identify areas where research and development could lead to major improvements in bulkhead construction and maintenance. Emphasis has been placed on areas in which an improvement could lead to major reassessment of present-day practices rather than on evolutionary development of current materials and methods.

A. Coatings

Present coatings for underwater protection of bulkheads must be applied before the structure is placed in its service environment. These coatings continue to be effective against corrosion from the sea water for a period of several months to several years. At that time, since there is no economical technique for recoating the underwater surfaces, alternative means for maintenance and repair of the bulkhead must be employed. An effective technique for underwater application of substantial coatings is needed.

Two approaches to the development of an underwater coating system seem to merit further research. The first approach is to develop a new coating that can be easily applied underwater, perhaps using straightforward application techniques such as brushing or spraying. The cementiferous paints discussed in Section IV are a step in this direction. A second approach is that of finding novel applications for presently available coatings. Local dewatering, maintained by a sealed container in which application and curing can proceed, is an example of such an application.

Since epoxy resin coatings have been found to be effective for protection after underwater application, this

ystem could be pursued to make it economically feasible. A possibility is a mixing nozzle for combination of the two-pack epoxy system just prior to application, coupled with a brush applicator or other spreader. Such a technique would permit more rapid, semi-continuous application of the epoxy coating to the bulkhead surface.

The above coatings are concerned with formation of a film to separate the bulkhead from the sea water. Other alternative mechanisms for coating protection are possible. For example, the corrosive oxygen concentration cell just below water level causes deterioration of sheet steel bulkheads. The traditional approaches to inhibiting this corrosion have been cathodic protection and/or a protective coating film. Another approach would be to balance the oxygen distribution throughout the depth of the underwater portion of the structure by removing the excess oxygen from the surface layer of water near the bulkhead. This approach might be accomplished, for instance, by a coating that adsorbed the dissolved oxygen in the water and bubbled it back into the atmosphere. This coating could be applied at the initial installation of the bulkhead and, since it would protect by a different mechanism, could outlast normal film coatings in effective lifetime.

B. Facing Systems

In many cases, a deteriorated bulkhead structure still has sufficient structural integrity to support its backfill loading, and maintenance and repair techniques are aimed simply at preventing further deterioration. Since coating underwater continues to be a problem, development of a nonstructural facing system to protect the bulkhead from further deterioration by physically separating it from the sea water may be a desirable alternative. The facing system would have to be lightweight so that little additional overturning moment would be added to the original bulkhead structure. The system might consist of an outer form and an inert filler material to seal the space between that form and the original bulkhead, as described in the discussion on repair techniques. Research might be devoted to

the development of economical materials and construction techniques for this type of facing repair system.

C. Composite Materials

Composite material systems generally are made up of two or more component materials, the combination of which improves upon the characteristics of the individual component materials. Two kinds of composite construction can be visualized for application to bulkhead construction.

One type of composite construction would simply apply the traditional materials from which shore protection facilities are constructed in such a way that the best available material was used in each particular zone of attack from the environment. This approach is summarized in Figure 42, where the three traditional materials for shore protection are evaluated in each of the six zones of marine environmental attack. This approach is a simple extension of the "composite construction" approach used for years in building docks, where wood piles are used in underwater areas and the superstructure above the water line is built of concrete. It has obvious advantages in that it places the most resistant material in the proper position for each kind of attack.

A second type of composite materials approach would require the development of new construction materials *per se*, composite on the microscopic scale only. Fiberglas reinforced plastics and plywood are examples of such composite materials. A materials combination to replace sheet-steel piling as a bulkhead material would need to have stiffness and strength characteristics near those of steel, and corrosion resistance characteristics near those of the noble metals. Two possible forms for the development of such composite materials are commonly used in other fields: fiber-reinforced matrices and laminated systems. An example of the first form for marine application might be continuous, oriented high-strength steel wires used to reinforce a matrix of a ductile, corrosion-resistant metal or ceramic. An example of a laminated system might be a low density core, surrounded by relatively thin layers of sheet-steel and

then covered with a thin layer of inert, continuous polymeric or ceramic coating for corrosion resistance. The number of possible combinations is unlimited, and the fiber reinforced or laminate system could even be combined with the zonal approach so that the outer coatings on the composite material would change to meet the demands of each environmental zone.

A survey of the combinations of composite materials that are presently available, with follow-on research to either adapt one of the materials available or to develop a new composite material tailored for the particular bulkhead applicable, would seem to be a fruitful area for research and development.

Figure 42

EVALUATION OF THREE BULKHEAD MATERIALS IN VARIOUS CORROSION ZONES

Zone	Problems	Order of Resistance to Attack	Most Economical (Initial Cost Plus Life Considerations)
Atmosphere	Attack by Air-Borne Corrosives	Concrete Steel Timber	Concrete
Splash	Rusting (Oxidation)	Concrete Timber Steel	Concrete
Tidal	Freeze-Thaw Wetting-Drying	Timber Concrete Steel	Timber
Active Electrolytic	Oxygen Concentration Cell	Timber Concrete Steel	Timber
Underwater	Erosion	All OK	Steel
Imbedded	Abrasion on Driving	All OK	Steel

XI. CONCLUSIONS

Selection of the most cost effective means for replacement, maintenance, or repair of sheet-steel bulkheads involves consideration of the following major factors:

- materials that will provide structural integrity in the bulkhead environment;
- installation cost;
- functional life or life extension;
- annual or periodic costs of maintenance; and
- mission life of the bulkhead.

When the mission life exceeds the functional life, an annual cost comparison of alternatives can be made, using the formulas in Section VII. An analysis should also be made of the environmental factors, including the economic, climatic, and other conditions that may favor or militate against the use of a material system. If the bulkhead is in good functional condition, the alternative courses of action are:

- annual maintenance;
- periodic maintenance; and
- no maintenance.

These alternatives should be compared on an annual cost basis, taking into consideration the life extension of the bulkhead offered by the use of the first two alternatives.

With the bulkhead approaching a failure condition, there are three general alternatives available:

- maintain as often as required to extend functional life a few more years;

- repair to provide several more years of life; or

- replace with a new structure.

These alternatives can be compared from a cost effectiveness standpoint by applying the formulas in Section VII. Maintenance, such as concrete patching, may be used to prevent wash-out and to patch small holes. If the bulkhead is inspected frequently and maintenance is performed as required, the bulkhead may be maintained for 1 to 5 additional years. Maintenance projects will eventually become more frequent, and the annual costs will become greater.

Repair techniques offer the prospect of 10 to 25 years of additional life at a cost somewhat less than replacement with a carbon steel piling bulkhead. The annual cost for a repair technique can be calculated and compared with other repair and replacement systems.

The replacement systems offer the prospect of long life and low initial maintenance costs. The special steels and carbon steel with cathodic protection or coating can endure for 25 to 35 years. Rip-rap walls will endure for at least as many years, but do have the disadvantage of restricting flexibility in the future utilization of the bulkhead area.

When the mission life is uncertain or less than the functional life of the bulkhead system to be employed, longer life or life extension may not be utilized. All alternative systems must then be compared over the mission life only. Under this condition, lower initial cost alternatives, such as annual maintenance or some repair techniques, may be the most cost effective systems to use.

Appendix

REFERENCES

Metals

Alumbaugh, Robert L. "Coatings for Steel Piling in Sea Water," Materials Protection, Vol. 3, No. 7 (July, 1964), pp. 34-36, 39-45.

________. Protective Coatings for Steel Piling: Results of 30-Month Tests. Technical Report R-194. Port Hueneme, California: U.S. Naval Civil Engineering Laboratory, 1962.

Alumbaugh, R. L., Brouillette, Carl V., and Fowler, A. L. Protective Coating for Steel Piling: Results of 6-Month Tests. Project NY 450 004-2, Technical Note N-309. Port Hueneme, California: U.S. Naval Civil Engineering Research and Evaluation Laboratory, 17 September 1957.

American Zinc Institute, Inc. Zinc as a Galvanic Anode... Underwater. New York: American Zinc Institute, Inc.

Applegate, L. M. Cathodic Protection. New York: McGraw-Hill, 1960.

Bethlehem Steel Corporation. Bethlehem Steel Sheet Piling. Catalog 433-C. Bethlehem: Bethlehem Steel Corporation.

________. Typical Installations of Bethlehem Steel Sheet Piling. Booklet 127-C. Bethlehem: Bethlehem Steel Corporation.

________. Typical Installations—Bethlehem Steel Sheet Piling. Booklet 1959-A. Bethlehem: Bethlehem Steel Corporation.

Brouillette, C. V., and Alumbaugh, R. L. Protective Coatings for Steel Piling: Correlation of Results of Parallel Test Exposures at Port Hueneme and Guam. Technical Report R-397. Port Hueneme, California: U.S. Naval Civil Engineering Laboratory, 1965.

Brouillette, C. V., and Hanna, A. E. Corrosion Survey of Steel Sheet Piling. Technical Report 097. Port Hueneme, California: U.S. Naval Civil Engineering Laboratory, 27 December 1960.

________. Second Corrosion Survey of Steel Sheet Piling. Technical Report R-467. Port Hueneme, California: U.S. Naval Civil Engineering Laboratory, August, 1966.

Bureau of Ships and American Zinc Institute. Zinc as a Galvanic Anode. Bureau of Ships and American Zinc Institute Symposium, 21-22 April 1955.

Burns, R. M., and Bradley, W. W. Protective Coatings for Metals. 2d ed. New York: Reinhold, 1955.

Butler, G., and Ison, H. C. K. Corrosion and Its Prevention in Waters. New York: Reinhold, 1966.

Corrosion Prevention and Control. Anti-Corrosion Manual. 4th ed. London: Corrosion Prevention and Control, 1962.

Drisko, Richard W., and Brouillette, C. V. "Comparing Coatings in Shallow and Deep Ocean Environments," Materials Protection, April, 1966.

Ebasco Services, Inc. Principles of Corrosion and Cathodic Protection. New York: Ebasco Services, Inc.

Evans, U. R. An Introduction to Metallic Corrosion. New York: St. Martin's Press, 1963.

Forgeson, B. W., Southwell, C. R., and Alexander, A. L. Corrosion of Metals in Tropical Environments: Part 3—Underwater Corrosion of Ten Structural Steels. Report 5153. Naval Research Laboratory, 8 August 1958.

Glikman, L. A. Corrosion—Mechanical Strength of Metals. London: Butterworths, 1962.

Humble, H. A. "The Cathodic Protection of Steel Piling in Sea Water," Corrosion, Vol. 5 (1949), p. 292.

Johnson, S. M. Deterioration, Maintenance, and Repair of Structures. New York: McGraw-Hill, 1965.

Kennedy, E. R., and Wilson, J. S. Marine Piling Corrosion: New York Harbor. The Port of New York Authority. Presented at National Association of Corrosion Engineers Conference, Miami Beach, Florida, April, 1966.

King and Gavaris Consulting Engineers. Bulkhead Sheet Pile Thickness Survey Report on Evaluation of Instruments and Techniques. Contract NBy 70326(ES). King and Gavaris Consulting Engineers, 15 September 1965.

________. Restudy, Existing Sheet Pile Bulkhead, Naval Air Station, Floyd Bennett Field, N.Y. Contract NBy 50996 (A&E). King and Gavaris Consulting Engineers, 6 November 1963.

________. Report of Investigation, Existing Sheet Steel Pile Bulkhead, Naval Air Station, Floyd Bennett Field, N.Y. Contract NBy 16982(ES). King and Gavaris Consulting Engineers, 30 June 1958.

Koshelev, G. G., and Rozenfeld, I. L. "Corrosion Stability of Low-Carbon and Low-Alloy Steels in Sea Water," translated by Foreign Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 1963.

LaQue, F. L., and Copson, H. R. Corrosion Resistance of Metals and Alloys. 2d ed. New York: Reinhold, 1963.

Larrabee, C. P. "Corrosion-Resistant Experimental Steels for Marine Applications," Corrosion, Vol. 14 (1958), p. 501.

Lattin, Benton C., "Steel Piling in Sea Water," Consulting Engineer, June, 1958.

Morgan, J. H. Cathodic Protection. London: Leonard Hill Ltd., 1959.

National Association of Corrosion Engineers. Bibliography of Books on Corrosion. 2d ed. Houston: National Association of Corrosion Engineers, 1966.

Peabody, A. W., "Corrosion at Sea," Ebasco News, July, 1965.

Pittsburgh Chemical Company. Pitt Chem Coating Guide for Piling. Revised. Pittsburgh: Pittsburgh Chemical Company, January, 1965.

Plesset, M. S., Bass, B. C., and Hickling, R. Cathodic Protection in Cavitation Damage. Report No. 85-10. Engineering Division, California Institute of Technology, November, 1958.

Priest, H. Malcolm, and Gilligan, John A. Design Manual for High Strength Steels. Publication Number ADUSS 02-1327. Pittsburgh: United States Steel Corporation, Research and Technology, 1965.

Rogers, T. H. The Marine Corrosion Handbook. Toronto: McGraw-Hill, 1960.

Scully, J. C. The Fundamentals of Corrosion. New York: Pergamon Press, 1966.

Shreir, L. L. Corrosion. Vol. 2 of Corrosion Control. Edited by L. L. Shreir. London: George Newnes Ltd., 1963.

Tomashov, N. D. Theory of Corrosion and Protection of Metals. New York: Macmillan, 1966.

Uhlig, H. H. Corrosion and Corrosion Control. New York: Wiley, 1963.

United States Steel Corporation. Mariner Steel Sheet and H Piling. Pittsburgh: United States Steel Corporation, May, 1964.

________. New, High Strength Steel Sheet Piling. Pittsburgh: United States Steel Corporation, August, 1963.

________. Part Plans or Sections of Piling Installations. Pittsburgh: United States Steel Corporation.

________. Protection of Piling in Marine Environments. ADUCO 25003-58. Pittsburgh: United States Steel Corporation.

________. Steel H-Piles. ADUCO 25002. Pittsburgh: United States Steel Corporation, January, 1962.

________. USS Steel Sheet Piling. ADUSS 25-2369. Seventh Printing. Pittsburgh: United States Steel Corporation.

________. USS Steel Sheet Piling. ADUCO 25010. Pittsburgh: United States Steel Corporation, August, 1963.

Wahlquist, Hugo W. "Long Term Tests with Various Coating Materials," Gas, March, 1958.

Concrete

The American Society of Agricultural Engineers. Concrete Slipform Canal and Ditch Linings. The American Society of Agricultural Engineers Standard: ASAE S289. Adopted June, 1965.

Bryan, Ross H. "Prestressed Concrete for a Sea Wall," Civil Engineering, April, 1961, pp. 54-55.

Dean, W. E. "Prestressed Concrete Sheetpiles for Bulkheads and Retaining Walls," Civil Engineering, April, 1960.

Gardner, Stephen V., and New, Dudley H. "Some Experiences with Prestressed Concrete Piles," Proceedings of the Institution of Civil Engineers (London), Vol. 18 (January, 1961), pp. 43-66, and Vol. 21 (April, 1962), pp. 867-891.

Hallmark, Dasel E. Innovations in Concrete for Harbor and Shore Construction. Reprinted by Portland Cement Association. (Presented at the American Society of Civil Engineers Water Resources Engineering Conference, Milwaukee, Wisconsin, May 13-17, 1963.)

Jachowski, Robert A. Interlocking Precast Concrete Block Seawall. New York: American Society of Civil Engineers, 1964. (Proceedings of 9th Conference on Coastal Engineering, Lisbon, June, 1964.)

Johnson, S. M. Deterioration, Maintenance, and Repair of Structures. New York: McGraw-Hill, 1965.

Lin, T. Y., and Talbot, W. J. "Pretensioned Concrete Piles—Present Knowledge Summarized," Civil Engineering, May, 1961.

MacLeay, Donald M. "Manufacturing Methods in Construction," Journal of the American Concrete Institute, Vol. 27, No. 9, May, 1956.

McGregor, T. H. "T-Shaped Concrete Sheet Piles Renew Deteriorated Bulkhead," Engineering News-Record, January 3, 1963, p. 33.

"On-Site Precasting," Concrete Construction, July, 1959, pp. 6-9.

Orchard, D. F. Properties of Materials. Vol. 1 of Concrete Technology. 2d ed. New York: Wiley, 1962.

Parsons, Donald A., and Apmann, Robert P. "Cellular Concrete Block Revetment," Civil Engineering, February, 1965, p. 66.

________. "Cellular Concrete Block Revetment," Journal of the Waterways and Harbors Division, American Society of Civil Engineers, Vol. 91, No. WW2, Procedural Paper 4311, May, 1965, pp. 27-37.

Pittsburgh Chemical Company. Pitt Chem Coating Guide for Hydraulic Structures. Revised. Pittsburgh: Pittsburgh Chemical Company, October, 1964.

Portland Cement Association. "Concrete Crib Retaining Walls," Concrete Information. Chicago: Portland Cement Association.

________. "Concrete for Hydraulic Structures," Concrete Information. Chicago: Portland Cement Association, 1960.

________. "Concrete in Sea Water," Concrete Information. Chicago: Portland Cement Association, 1948.

________. Concrete Piles. Chicago: Portland Cement Association, 1961.

________. Concrete Shore Protection. Chicago: Portland Cement Association, 1955.

________. "Freezing and Thawing of Concrete," Concrete Information. Chicago: Portland Cement Association, 1961.

________. Soil-Cement Slope Protection for Earth Dams. Chicago: Portland Cement Association.

________. Suggested Specifications Soil-Cement Slope Protection for Earth Dams. Chicago: Portland Cement Association.

________. Water Control. Chicago: Portland Cement Association, 1959.

"Prestressed Beams Shore Drydock Walls," Engineering News-Record, October 20, 1960, pp. 42-43.

"Quick-Set Cement Grout Sets Up Under Water," Engineering News-Record, March 14, 1963, p. 49.

Scholer, C. H. Study of Corrosion Problems in Naval Reinforced Concrete Structures Subject to Salt Water Exposure. Contract NBy-3198. Port Hueneme, California: U.S. Naval Civil Engineering Laboratory, June, 1962.

Sellner, E. P. Use of Concrete for Shore Protection. Chicago: Portland Cement Association.

Tallamy, Bertran D., Associates. Evaluation of Methods of Replacement of Deteriorated Concrete in Structures. Report 1, National Cooperative Highway Research Program. Highway Research Board, 1964.

Wood and Other Materials

Department of the Navy. Marine Biology Operational Handbook. NavDocks MO-311. Department of the Navy, Bureau of Yards and Docks, May, 1965.

Hunt, G. M, and Garratt, G. A. Wood Preservation. 2d ed. New York: McGraw-Hill, 1953.

Scofield, W. F., and O'Brien, W. H. Modern Timber Engineering. Revised by T. E. Brassell. New Orleans: Southern Pine Association, 1954.

Stamm, A. J. Wood and Cellulose Science. New York: Ronald Press, 1964.

Timber Engineering Company. Timber Design and Construction Handbook. New York: F. W. Dodge Corporation, 1956.

U.S. Department of Agriculture. Wood Handbook. Handbook No. 72. The Forest Products Laboratory, Forest Service, U.S. Department of Agriculture, 1955.

Mineral Fiber Products Bureau. Design Manual for Asbestos—Cement Canal Bulkheads. New York: Mineral Fiber Products Bureau, 1965.

Van Lookeren Campagne, I. R. J. P. A. "Use of Nylon in Hydraulic Engineering," Civil Engineering, January, 1963, pp. 31-33.

Shore Protection Structures

Army Corps of Engineers. Shore Protection Planning and Design. Technical Report No. 4. Department of the Army, Corps of Engineers, Beach Erosion Board, Office of the Chief of Engineers, 1961.

California Department of Public Works. Bank and Shore Protection in California Highway Practice. California Department of Public Works, Division of Highways, November, 1960.

Department of the Navy. Design Manual Waterfront Operational Facilities. NavDocks DM-25. Updated through February, 1966. Department of the Navy, Bureau of Yards and Docks, November, 1961.

________. Maintenance of Waterfront Facilities. NavDocks MO-104. Department of the Navy, Bureau of Yards and Docks.

Hall, Jay V., Jr. "Structure for Shore Protection," Civil Engineering, July, 1963, pp. 38-41.

Minikin, R. R. Winds, Waves, and Maritime Structures. 2d ed. London: Griffin, 1963.

Quinn, A. D. Design and Construction of Ports and Marine Structures. New York: McGraw-Hill, 1961.

Thorn, R. B. The Design of Sea Defence Works. London: Butterworths, 1960.

Wiegel, R. L. Oceanographical Engineering. Englewood Cliffs, New Jersey: Prentice-Hall, 1964.

Economics and Costs

Brouillette, C. V., and Alumbaugh, R. L. Protective Coatings for Steel Piling: Correlation of Results of Parallel Test Exposures at Port Hueneme and Guam. Technical Report R-397. Port Hueneme, California: U.S. Naval Civil Engineering Laboratory, August, 1965.

Grant, E. L. Principles of Engineering Economics. 3d ed. New York: The Ronald Press Company, 1950.

King and Gavaris Consulting Engineers. Report of Investigation, Existing Sheet Steel Pile Bulkhead, Naval Air Station, Floyd Bennett Field, N.Y. Contract NBy 16982(ES). King and Gavaris Consulting Engineers, 30 June 1958, pp. 15-20.

________. Restudy, Existing Sheet Pile Bulkhead, Naval Air Station, Floyd Bennett Field, N.Y. Part II. Contract NBy 50996 (A&E). King and Gavaris Consulting Engineers, 6 November 1963.

Maguire, Charles A., & Associates. Thames Street Renewal Area Bulkhead Study. 1965, pp. 8-22.

United States Steel Corporation. Mariner Steel Sheet and H Piling. Pittsburgh: United States Steel Corporation, May, 1964, pp. 5-7.

United States Navy. Inspection Reports 1-50. Contract NBy 77539. United States Navy, Eastern Division, Naval Facilities Engineering Command, October, 1966.

Wisconsin Protective Coating Corporation. Corrosion Resistant Coating. Bulletin 52. Wisconsin Protective Coating Corporation.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Peat, Marwick, Livingston & Co.	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

Cost Effectiveness in Sheet-Steel Bulkhead Replacement, Maintenance, and Repair

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report covering period of August 31, 1966-December 31, 1966

5. AUTHOR(S) (Last name, first name, initial)

Fettig, Kenneth G.
Jones, Russel L.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 31, 1966	186	100

8a. CONTRACT OR GRANT NO. N62319 67C 0040 (NBy 77589 (ES))	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. Y-F015-15-07-004	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Eastern Division Naval Facilities Eng'g Command

13. ABSTRACT

Presented in this report are the results of a study to determine what materials and methods can be economically used in sheet-steel bulkhead installation, maintenance, and repair. Several materials and methods are investigated to determine if their use will aid in extending bulkhead life. Mathematical models of the cost of application of the more promising systems are compared with the cost of a carbon steel bulkhead. Eight systems that appear to be cost effective are examined in detail. The most favorable conditions for use of these systems are discussed particularly in reference to bulkhead maintenance and repair work that was concurrently conducted at the Naval Air Station, New York.

Unclassified

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Steel Bulkhead						
Cost Effectiveness						
Maintenance						
Installation, Bulkheads						
Repair, Bulkheads						
Operations Research						
Methods and Materials						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ______."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ______."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ______."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

Unclassified